UNITED
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PROGRAMME

Jordan

GENERAL REPORT ON THE GROUND-WATER INVESTIGATION OF THE AZRAQ BASIN

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Prepared for
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ABSTRACT

The area investigated is a desert basin with interior drainage that covers an area of about 12,800 square kilometres in north-eastern Jordan. Springs issuing in the centre of the basin at El-Azraq form an oasis in the desert and support a very limited local agricultural and salt-production economy. Potable water is pumped from one of the springs through a pipeline to the city of Irbid and used as a supplementary municipal supply.

The geologic formations exposed in the basin range in age from cretaceous to recent, and include sedimentary and volcanic rocks. Both types of rocks yield water to the springs at El-Azraq and to wells at scattered places in the basin. The wells tap both artesian and unconfined ground water, but specific capacities and permeabilities generally are low.

Exploratory drilling and testing in the basin show that aquifers in the deep-lying Kurnub sandstone are at too great a depth to be economically exploited for water, and that the permeability of the formation is low in the Azraq area. The overlying Ajlun Series does not contain ground water in significant quantities. The lower aquifers in the next overlying Belqa Series of sedimentary rocks probably are at too great a depth to be exploited under present economic conditions. Withdrawal of ground water from the aquifers at intermediate and shallow depths in the sedimentary and volcanic rocks is feasible, but the perennial supply is limited and withdrawals of any magnitude will reduce the discharge of the springs at El-Azraq.

The aquifers at intermediate and shallow depth receive recharge by direct infiltration of precipitation and by seepage from some reaches of the intermittent stream beds. The ground water moves downgradient through the aquifers toward the topographically low central area at El-Azraq. Ground water is discharged naturally by the springs at El-Azraq and by evapotranspiration; a small quantity is discharged by wells.

Studies made from 1955 through 1958 of the water-resources potential of the basin suggested that large quantities of ground water are perennially available for extensive agricultural development by irrigation, or for exportation from the basin. A pre-investment field survey made by the Special Fund of the United Nations from January 1962 to May 1964 indicated that the perennially available water resources of the basin are very limited, that they are being used at the optimum rate and that any additional large-scale development would upset the water-resources regimen and economy of the basin.

The amount of ground water perennially available for use was estimated by measuring and computing the total discharge from all sources at El-Azraq. By relating the total annual discharge to the total annual precipitation within the basin, the quantity of recharge that reaches the water-table was estimated to be about 2 per cent of precipitation. Quality-of-water studies indicated that about 80 per cent of the total recharge is derived from the volcanic rocks that underlie the northern part of the basin. It was estimated that the total amount of ground water discharged from the shallow aquifers is 2,335 cubic metres per hour (m^3/hr). However, because of various limiting factors, only about 1,200 m^3/hr of this amount is perennially available for use. This is much less than the amount estimated to be perennially available for use during previous studies.

Chemical analyses showed that much of the ground water is of marginal or unsuitable quality for irrigation because it has a high sodium and salinity hazard. Most of the soils in the area are too thin or too saline to successfully support irrigation agriculture, especially if water of poor quality were to be used for irrigation. In most places, special leaching and drainage practices would be necessary in order to reclaim additional land for agriculture. Water derived from the area of volcanic rocks in the north is the only water of suitable quality for either irrigation or domestic use.

Danger of the encroachment of salt water from the brine field at El-Azraq into the central springs prohibits large additional withdrawals of water from the springs or from wells near the springs. The ground water of good quality that is perennially available from the area of volcanics should be reserved for exportation from the basin if needs for emergency municipal supplies arise in other parts of Jordan. Should the Jordanian Central Water Authority decide to drill for emergency water-supplies, the drilling sites should be restricted to the areas in the northern part of the basin that are delineated in this report. Provisions should be made to relocate or support the population at El-Azraq if too large a part of the perennial ground water-supply is developed and exported. The resulting major reduction of the spring discharge would undermine the local economy.

Weir installations at the springs should be maintained and daily measurements of the spring discharges should be continued. Daily checks of the quality of the spring water should be continued by measurement of electrical conductivity or by determination of chlorides. Such measures are necessary to

detect any critical reduction of discharge or deterioration of quality of the water from the springs.

Indications are that, in addition to the ground water perennially available, a large volume of water is contained in storage in the shallower geologic formations—principally in the Belqa Series. If the Government of Jordan should decide to mine the stored ground water and export it out of the basin for municipal or industrial supplies, relatively large quantities probably could be pumped for a long period of time. Additional exploration and testing of the aquifers would be necessary before such a programme could be initiated.

INTRODUCTION

A. Purpose and organization of the project

1. The project was initiated following an official request made by the Government of Jordan to the Special Fund of the United Nations* on 27 September 1960 for assistance in studying the water resources of the Azraq area. On 2 November 1961, representatives of the Government of Jordan, the Special Fund of the United Nations and the United Nations signed a plan Azraq Basin in Jordan. The signatories of the document were: Mr. Bahjat Talhouni, Prime Minister and President of the Board of Directors of the Central Water Authority; Sir Eric Franklin, Acting United Nations Resident Representative; and Mr. Arthur Goldschmidt, Director of Special Fund Activities for the United Nations. The United Nations Department of Economic and Social Affairs was appointed executing agency for the project.

2. Some previous investigators in Jordan, impressed by the relatively large discharge of water from the springs in the centre of the Azraq Basin, had speculated that enough ground water might be available to warrant extensive agricultural development by irrigation from wells. During the period from 1955 through 1958, discharge measurements were made of the Azraq springs, some exploratory drilling was done in the basin, agricultural studies were made and estimates were made of the quantity of water available for intensified development. However, the results of the studies were not satisfactory, and some authorities felt that the estimates of the quantity of perennially available ground water were overly optimistic. Therefore, it was decided that a pre-investment survey was needed to make a firm appraisal of the dependable water resources of the basin.

3. The basic purpose of the project was to assess the ground-and-surface-water potential of the Azraq area, to detect existing and potential problems, and to recommend the best uses for the water resources. In addition, training was to be provided to Jordanian personnel in drilling techniques, methods of ground-water exploration and related studies.

4. The Special Fund provided a staff of international specialists, fellowships for selected Jordanians, a variety of equipment and supplies that included a large rotary drilling rig, and funds for required subcontracts. The Government of Jordan, through its Central Water Authority, furnished a counterpart staff of Jordanian specialists, administrative and clerical personnel, a team of skilled and unskilled labourers, offices and other supporting facilities, and a wide variety of auxiliary equipment and supplies.

5. The names and post titles of the Special Fund personnel, as well as the durations of their service with the project, are given below:

(a) Mr. B. R. Hudson, project manager, January 1962-January 1964;

(b) Mr. G. R. Wilson, hydrologist, October 1962-May 1964;[1]

(c) Mr. J. A. Hoagland, drilling superintendent, October 1962-September 1964;

(d) Mr. W. J. Kirby, tool pusher, May 1963-April 1964;

(e) Mr. C. Bleys, geologist, October 1963-March 1964;

(f) Mr. H. Buser, hydrogeologist, December 1962-July 1963;

(g) Mr. M. A. Aal, agronomist, January 1963-January 1964;

(h) Mr. J. D. Whyte, administrative officer, June 1963-May 1964.

6. The names and durations of service of the project representatives of the Jordanian Government are given below:

(a) Mr. Kamel A. Kawar, May 1962-September 1962 and March 1963-May 1964;

(b) Mr. Omar A. Dokhgan, October 1962-February 1963;

(c) Mr. Oliver H. Folsom, 3 weeks in February 1963.

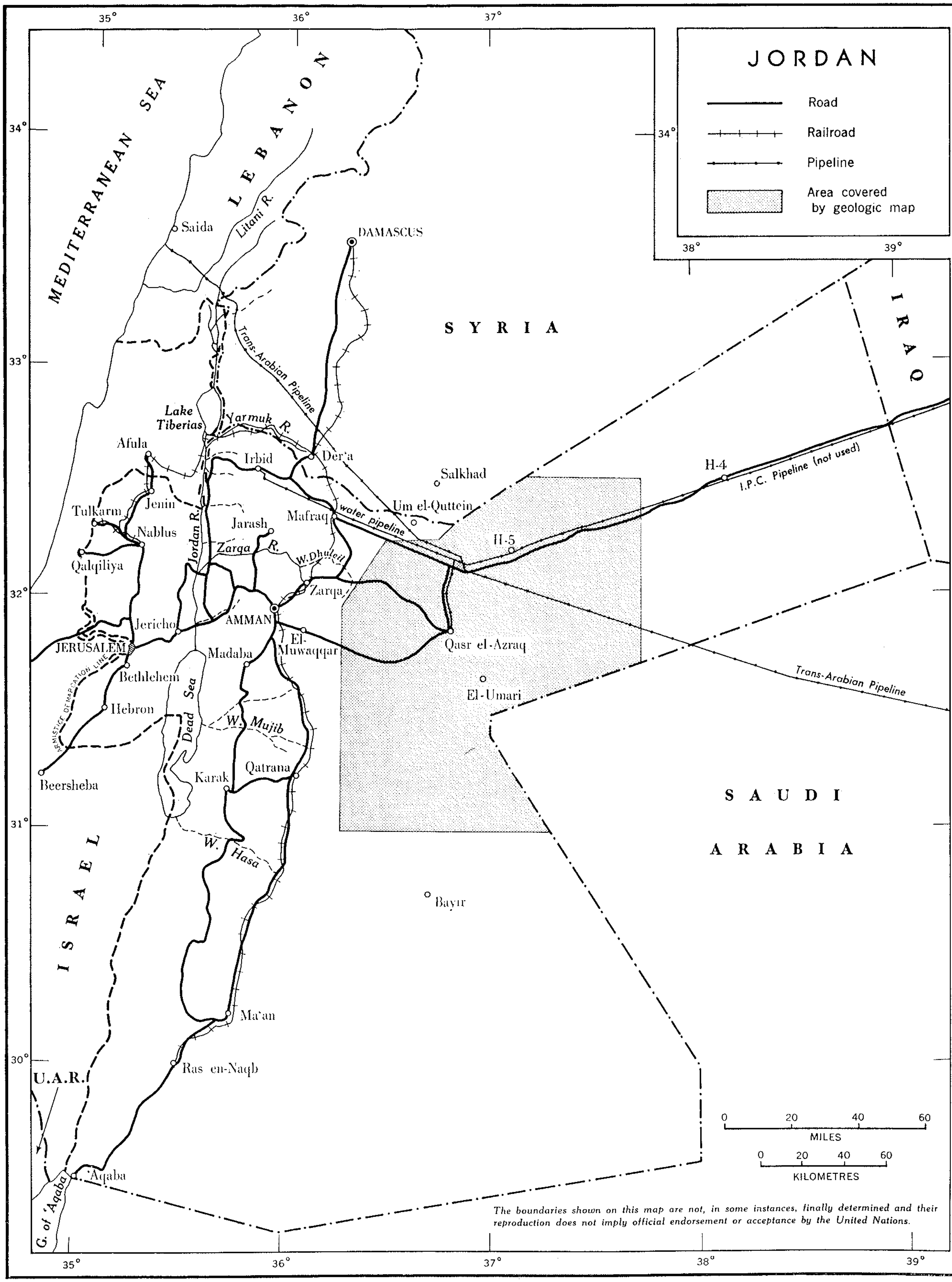
7. Other Jordanian personnel were Mr. Ahmed Kilani, Mr. Yahya Habash, Mr. Mohammed Abu Ajamieh, Mr. Taher Nasseredin, Mr. Yousef Azzeh, Mr. Abdullah Bazian and Mr. Fahid Qaqish.

8. The members of the Jordanian Central Water Authority, which was the government department concerned with the Azraq project, were Mr. Oliver H. Folsom, Director General; Mr. Omar A. Dokhgan, Deputy Director General; Mr. Salim Tannous, Chief of Drilling Operations; Mr. Kamel A. Kawar, Chief of Geology

* The United Nations Special Fund and the Expanded Programme of Technical Assistance were merged into the United Nations Development Programme on 1 January 1966.

[1] Mr. Wilson served as acting project manager from June 1963 to September 1963, and again from February 1964 until completion of the project in the summer of 1964.

MAP 1. INDEX MAP SHOWING AREA DESCRIBED IN THIS REPORT



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Division; and Mr. Ibrahim Attour, Chief of Hydrology Division.

9. In January 1962, Special Fund operations began with the arrival of the project manager. Offices were set up in Amman, and a warehousing facility was organized at a storage yard of the Central Water Authority. To facilitate field-work, a base camp was established slightly west of the villages Druze and Sheshan, near the springs at El-Azraq. Supplies were stored in a small warehouse at Sheshan and also at the Shomari Agricultural Experimental Station.

10. During the investigation, the origin, quantity, movement, availability and use of the water resources of the Azraq Basin were studied, and estimates of evapotranspiration were made. Chemical analyses of the water were made; relations of the chemical composition of the water to the geology and hydrology of the area were studied; and the suitability of the water for different beneficial uses was evaluated. Soil surveys were undertaken in selected areas.

11. This programme of work continued until late 1963, at which time a review of the findings led to a decision to terminate the investigation. All field operations were completed by May 1964.

B. Description of the area

12. The Azraq Basin is a roughly saucer-shaped topographical depression covering an area of approximately 12,800 square kilometres. Most of the basin is in north-eastern Jordan, but part extends northward into Syria. The south-eastern edge of the basin extends to the border of Saudi Arabia and the western edge is about 20 kilometres from Amman, capital of Jordan. An index map of Jordan (map 1) shows the area discussed in this report.

13. From the approximate centre of the basin at El-Azraq, where the altitude is about 500 metres above mean sea level, the land surface slopes gently upward to the crests of the hills bordering the basin. North of Salkhad, Syria, elevations along the topographical divide reach 1,800 metres above sea level. The westerly topographical divide near Amman is about 900 metres above mean sea level, and along the southern and eastern borders of the basin, altitudes generally range from 600 to 900 metres. Topographical relief is small in the centre of the basin, but increases toward the drainage divides. As described by Quennell, "It today represents a desert cycle topography that has rapidly reached the senile or late mature stage because of the easy erodability of the chalks of the Belga Series."[2] The principal road follows the unused Iraq Petroleum Company (IPC) pipeline across the northern part of the basin. A short stretch of graded road was recently constructed northward from El-Azraq, along the Azraq-Irbid water pipeline. Travel elsewhere in the region is either across the open desert or along tracks made by occasional vehicles.

14. The basin is predominantly a barren desert, except for a small area around El-Azraq, where ground water discharging through springs supports a limited amount of marsh vegetation. Phreatophytes (water-loving plants) and halophiles (salt-tolerant plants and shrubs) comprise most of the marsh vegetation; a few palm and other trees grow near the spring and swamp area. Small cultivated areas are irrigated by water from the springs and a few wells. The climate is arid over most of the basin and only a small region along the north-western drainage divide receives sufficient rainfall to permit a very low level of dry-farming. Over the rest of the basin, the limited rainfall supports only scattered desert shrubs and grasses.

15. Precipitation averages only about 84 millimetres per annum, most of which occurs during erratic and unevenly distributed storms that may cover only a small part of the entire basin. No perennial streams or permanent bodies of surface water, except for the springs and pools at El-Azraq, are found within the basin. After the infrequent storms, some water runs off in intermittent stream channels and eventually collects in topographical depressions (playas), where it evaporates in a few months. A very small percentage of the rainfall, estimated to be less than 2 per cent per annum, seeps downward through the surface material of the uplands and the stream beds and replenishes the ground water in the underlying geologic formations. The ground water moves slowly through the rocks in a downgradient direction and eventually is discharged through springs and seeps at El-Azraq.

16. The soils of the basin generally are of poor quality. Burdon described them as grey desert soils usually mantled by lag-gravels, or by a desert pavement of flint or basalt, or by lime concretions, depending largely on the composition of the parent rock over which they had formed.[3] The northern part of the area is underlain by partly eroded basalt flows, which extend southward to El-Azraq.

17. According to the 1961 census, about 1,100 people live in the villages of Druze and Sheshan near the springs at El-Azraq and at the Shomari Government Farm just south of Sheshan Springs.[4] A few people live at the small police-posts at Sheshan, at El-Umari and at H-5, a station on the unused IPC pipeline. In addition, a few thousand Bedouin tribesmen lead a nomadic life in the region.

18. The only economic activity, aside from the localized dry-farming mentioned above, consists of crude

[2] A. M. Quennell, "The Geology and Mineral Resources of (Former) Trans-Jordan," Colonial Geology and Mineral Resources, vol. 2, No. 2 (London, 1951), p. 87.

[3] D. J. Burdon, *Handbook of the Geology of Jordan (to Accompany and Explain the Three Sheets of the 1:250,000 Geological Map of Jordan East of the Rift by A. M. Quennell).* Government of the Hashemite Kingdom of Jordan (Amman, 1959), p. 20.

[4] See map 3 in pocket.

salt production near Druze and Sheshan, and a minor amount of agriculture in the area watered by the springs. Although there is some tourist interest in the five or six old castles and ruins found in the basin, this contributes little to the economy of the region because the touring parties are self-sufficient and rarely remain overnight in the desert.

C. Procedure of the investigation

19. The field-work on which this report is based was begun in the spring of 1962 following the initial organization of staff and facilities. Records of previously drilled wells were collected and studied; information on total depth, depth to water, geologic source of water, rate of discharge and water-level drawdown was recorded when available. The surficial geology was mapped and sites were chosen for new test holes. Weirs were installed on the springs at Druze and Sheshan, and daily measurements of discharge were made. Climatological data were collected at a weather-station that was set up for that purpose at the Azraq base camp. Water-levels were measured weekly in three observation wells to determine seasonal fluctuations of the water-table. During the investigation, the depth to water was measured in selected wells and test holes to provide data for a map showing water-table contours. The altitude above mean sea level of the land surface and measuring points at the wells were determined by spirit leveling or from published topographical maps.

20. Cable-tool drilling rigs and a Portadrill air-rotary rig were used to explore the shallower aquifers and to provide supplemental information on the geology. In October 1962, the large rotary drilling rig provided by the Special Fund was set up at El-Azraq and a test hole was drilled into the deeper aquifers. The drilling programme was supervised by the expatriate staff and the holes were logged by geologists of the Central Water Authority. The logs of the test holes and wells were used in the construction of a geological map and two geological cross-sections. Records of most of the previously drilled wells and of the wells drilled during the project were selected for publication in this report. Electric and gamma-ray logs were run on selected wells.

21. Pumping tests, slug-injection tests and bailer tests were made on some of the wells to provide data on the hydrologic properties of the water-bearing materials. Samples of water were collected from representative wells and from the springs at El-Azraq. The samples were chemically analysed in the project laboratory at Amman and the data were used to construct a chemical-quality-of-water map. Soil studies were made, and existing agricultural and irrigation practices were investigated.

22. The geological and hydrological field data were recorded on aerial photographs and then transferred to overlays. The overlays were revised and redrafted to final form and reduced in scale at United Nations Headquarters. Co-ordinates on the geological and other maps are based on the Palestine grid system.

23. The Jordanian Government, through its contribution in funds, made available to the project a new two-storey building on Jebel Weibdeh in Amman. These accommodations provided ample space for the experts' offices, and for administrative, technical and clerical offices, a laboratory and a drafting room. A second building on the same premises had a garage, an office for the transportation and warehouse clerk, and extensive storage space. In addition, a large concrete warehouse was constructed at the Wadi Sir yard of the Central Water Authority on land made available by the Authority. After December 1962, all drilling equipment, materials and spare parts were stored in this building.

24. The field base camp was established about 2 kilometres south-west of the village of Druze (see map 3). One house-trailer had been installed at this site in May 1962 for use as an office for project personnel. After full field operations were begun in October 1962, the camp facilities were enlarged by the addition of 3 more house-trailers and 15 tents (14-by-14-foot size), which were occupied by the agronomy, drilling, geology and hydrology sections. An 18-by-45-foot army tent was set up for use as an office; mess tents were erected; and water, electricity and refrigeration facilities were installed. A regularly scheduled courier service travelled between Amman and Azraq 4 times a week. To support field operations, the United Nations provided a fleet of transport vehicles that consisted of 4 pick-up trucks, 3 power wagons, a 9-passenger carry-all, a 4-ton truck, two 6-ton trucks and a sedan. Well-casing and drilling materials were stored in warehouses in the village of Sheshan and at the Shomari Agricultural Station.

25. Excellent co-operation was received from the Jordanian Government's project representatives, from personnel of the Central Water Authority, and from the Jordanian professional and other personnel who were connected with the project. Many individuals with bilateral aid missions and private firms assisted with various phases of the work, including the Federal Republic of Germany's Geological Survey Mission, under Mr. F. Bender and Mr. G. van den Boom, was particularly co-operative. Hunting Technical Services Limited and Sir M. MacDonald and Partners, United Kingdom consultants to the Central Water Authority, kindly provided a draft copy of their "hydrogeological survey of the east bank of the River Jordan," prepared by Hunting Technical Services Limited during 1964. Mr. David J. Burdon and Mr. Harry Underhill of the Food and Agriculture Organization (FAO), and Mr. Norman B. Brown of Hunting Technical Services Limited furnished much useful information and gave material assistance in evaluating the geohydrological field data. Mr. Kamel A. Kawar, Chief of the Ground-water Division of the Central Water Authority, col-

lected additional field data during November 1964 and made it available to United Nations Headquarters. The assistance of all these individuals and organizations is gratefully acknowledged.

D. Summary of previous and concurrent investigations

26. A report by Ionides and Blake contains a comprehensive discussion of the ground-water resources of (Former) Trans-Jordan, but makes only brief mention of the Azraq Basin.[5] Quennell and Burdon also discussed the ground-water resources of Jordan and mentioned the Azraq area in the reports previously cited. Burdon described the water-bearing properties of the various geologic formations. In addition, a report by McKelvey contains a section on the regional ground-water resources of Jordan.[6]

27. The first attempt at development of the Azraq area was made in 1951 by the United Nations Relief and Works Agency (UNRWA), which established an Azraq pilot scheme to investigate the possibility of developing agricultural resources for the settlement of refugees. A shallow well was dug near the village of Druze and two refugee families were settled. In 1952, however, there was a change in UNRWA administrative policy regarding direct operations and the project was abandoned.

28. In 1955 the Jordan-United States Joint Fund for Special Economic Assistance authorized an investigation of the potential land and water resources of the Azraq area and designated it the Princess Alia Project. The investigation was undertaken by Baker-Harza Engineers (Michael Baker, Jr., Inc., Rochester, Pennsylvania; and Harza Engineering Co., Chicago, Illinois), with assistance from time to time from specialists associated with the United States Operations Mission to Jordan and from specialized agencies of the United Nations, notably FAO.

29. Baker-Harza submitted a reconnaissance report in December 1955, an interim report in August 1956 and a definitive report in October 1958. The latter is the one referred to herein as the Baker-Harza report. It contains plans for extensive agricultural development in the area, involving a capital investment of over US $5 million. Concurrent investigations[7] by Mr. J. L. M. Solignac, a ground-water geologist for FAO, were even more optimistic. Because of reservations as to the feasibility of the plans by some professional personnel, both Central Water Authority and foreign experts, the Government of Jordan requested a pre-investment survey, which was the mission of the Azraq Ground-water Project.

30. The reports by Baker-Harza and Solignac indicate that a large quantity of ground water is perennially available for exploitation in the Azraq Basin, but they do not present satisfactory supporting data. The findings of the Special Fund study were that only a very limited quantity of ground water is perennially available and that additional large-scale exploitation would upset the water-resources regimen and economy of the basin. Accordingly, the findings and recommendations of the Baker-Harza and Solignac studies are discussed here in an attempt to clarify the discrepancies.

31. The Baker-Harza report states that, "Inasmuch as it is generally accepted that from 5% to 20% of precipitation is ultimately available as ground water, an estimated 32,000,000 to 240,000,000 m^3 (in addition to the gauged spring flow) is still available for development, provided it can be located and utilized."[8] This statement is unsupported by available data and such high percentages could apply only in favourable areas that have ideal combinations of sandy soil, high rainfall and slow surface drainage. During the Special Fund study, the annual recharge in the Azraq Basin was computed by relating the total annual discharge at El-Azraq to the total annual precipitation within the basin; the total annual recharge was thus estimated to be about 2 per cent of precipitation.

32. In his reports,[9] Solignac made an analogy between the Azraq Basin and Chott Chergui, a basin of interior drainage in the Oran highland plains of Algeria, and stated that "Azraq is more important than Chott Chergui" (from the standpoint of water-resources potential). Comparison of data for the two basins does not support this statement. According to Drouhin, the area of Chott Chergui is about 40,000 square kilometres and it has a mean annual rainfall of 250 millimetres.[10] This gives an annual volume of some 10^{10} cubic metres of precipitation, which is a much larger volume than the Azraq Basin receives. Also, Drouhin mentioned ". . . a special geological circumstance (the presence of a transgression of heavily fissured Cenomanian limestone over a whole variety of formations)," which indicates that recharge charac-

[5] M. G. Ionides, and G. S. Blake, *Report on the Water Resources of Transjordan and Their Development.* U.K. Crown Agents for the Colonies (London, 1939).

[6] V. E. McKelvey, *Investigations Needed to Stimulate the Development of Jordan's Mineral Resources.* United States Geological Survey and United States International Cooperation Administration (Washington, D.C., 1959).

[7] J. L. M. Solignac, *Progress Field Examinations of Azraq. Report to the Government of Jordan* (Amman, 1956); *The Development Possibilities of the Azraq Area. Report to the Government of Jordan* (Amman, 1956); "Report on a Mission to Chott Chergui (Algeria) With a View to Draw Analogies Between the Chergui Problem and the Azraq Problem in Jordan" (Amman, 1956), typewritten report.

[8] Michael Baker, Jr., Inc. and Harza Engineering Co., *Princess Alia Project, Definitive Plan Report (Azraq)* (Amman, 1958), p. 118.

[9] Especially in his "Report on a Mission to Chott Chergui (Algeria) . . .", op. cit.

[10] G. Drouhin, "Reactions on the Hydrogeological Balance of the Exploitation of Underground Water Resources," paper prepared for the United Nations Educational, Scientific and Cultural Organization Symposium on Arid Zone Hydrology, held in Ankara, April, 1952 (Paris, 1953).

teristics were considerably superior to those in most of the Azraq Basin. These data indicate that total ground-water recharge for Chott Chergui is much greater than recharge in the Azraq Basin. Drouhin estimated that recharge to the ground-water reservoir in the Chott Chergui was at least 500 million cubic metres per year, which is about 25 times the value obtained for the Azraq Basin during the Special Fund study. The above data indicate that the Chott Chergui Basin has a much greater perennial ground-water potential than the Azraq Basin and that the two basins cannot be compared on a quantitative basis.

33. The total discharge of the major springs at El-Azraq was reported by Baker-Harza as 3,640 cubic metres per hour (m^3/hr),[11] a much larger quantity than the total spring discharge of 1,600 m^3/hr measured during the Special Fund study. Most of the original weir records of the Baker-Harza investigations cannot be located. As a result, it is difficult to assess accurately the disparity between the results obtained during the two investigations. The largest discrepancy was for the Sheshan South pool, for which Baker-Harza reported a discharge of 1,756 m^3/hr more than that measured by the Special Fund. Also, their reported discharge from the Baker-Harza Canal was 384 m^3/hr more than was measured by the Special Fund. The sum of these two excess quantities of discharge is about the same as the difference between the total spring discharge reported for both studies. Indications are that during the Baker-Harza study, the weirs on the Sheshan South pool and the canal were submerged (or "drowned"). Thus, the weirs did not give correct readings for computations of discharge. At the beginning of the Special Fund study, the crests of the weirs on the Sheshan pools were placed at a greater height in order to give proper aeration of the nappes and accurate readings, and the weir on the canal was relocated to give more accurate readings (see paras. 93-123 of this report).

34. In *The Development Possibilities of the Azraq Area*, Solignac contended that if the water-level of the Azraq pools could be lowered, either by drainage or pumping, large additional amounts of water would be discharged from the springs. Such an increase in discharge would be only temporary. Lowering of the head would act hydraulically to permit freer discharge and, at the same time, would make available additional water from storage. However, over a period of time, the water-level in the aquifers would stabilize at a lower level and equilibrium conditions would be re-established. Conversely, increasing the head would have a reverse effect and water would be added to storage, but over a relatively short time equilibrium again would be established. Only the quantity of water that enters the aquifers feeding the springs can be discharged from them and lowering the head will not alter this quantity of recharge.

35. The proposition by Baker-Harza that the springs in the Sheshan area are fed primarily from deep-seated aquifers[12] is disputed by the fact that the temperature of the spring water is normal for the shallow ground water in that area. In well AZ-1, ground water from the deep aquifers had a much higher temperature than the spring water. Also, the geochemical characteristics of the spring water are not consistent with the hypothesis of a major deep-seated source.

36. Between August 1962 and June 1964, Hunting Technical Services Limited made a hydrogeological survey of a 4,500-square-kilometre area that is adjacent to the Azraq Project area on the north-west and completed a draft report of their work in 1964. The final report will be accompanied by maps showing hydrogeological and structural features at a scale of 1:100,000.

37. Concurrently with the Special Fund project, Mr. F. Grünberg and Mr. F. S. Dajani of the Federal Republic of Germany's Geological Survey Mission in Jordan made a soils survey of the lower Wadi er-Ratam area and prepared a report in 1963. Their report is quoted and referred to in subsequent sections of this report.

38. Construction was begun on the Azraq-Irbid water pipeline in October 1962 under the direction of the Central Water Authority. The project consisted of removal and cleaning of a section of the unused IPC pipeline, re-laying the pipe from El-Azraq and installation of three high-lift pumps in the North Pool of Druze Springs.[13] An additional pipeline and a low-lift pump were installed to bring supplementary water from the Ein Qasiyah Pool of Sheshan Springs. Design capacity of the main Azraq-Irbid pipeline is 350 m^3/hr. The project was completed in December 1963.

E. Consultants on the Project

39. The Special Fund retained Mr. Munib Masri of the Jordan Engineering and Geological Services for a 10-day period in March 1962 to assist in geological field reconnaissance and subsurface geological correlation between the Azraq Basin and adjacent areas.

40. In September 1962, the Government of Jordan requested the Special Fund to undertake an additional engineering feasibility study of Azraq. At that time, the Special Fund experts in the field at Azraq felt that not enough basic data had been collected to warrant such a study. As a result, Mr. James J. Geraghty, consultant on hydrogeology to United Nations Headquarters, went to Jordan to make an appraisal of the situation. He remained in Jordan from 28 October to 7 November 1962, at the end of which time he submitted a report on his findings entitled, "Report to the Jordan Development Board on the Azraq Ground-water Pro-

[11] Baker and Harza, op. cit., p. 117.

[12] Ibid., p. 134.

[13] See maps 1 and 2. Map 2 in pocket.

ject." It ıt it was premature ıility study at that time, but that it might be possible to accelerate certain phases of the current programme by the addition of more manpower and equipment. Accordingly, he recommended the recruitment of three more experts—a driller-tool-pusher, a geologist and an administrator; also, one additional pick-up truck and one 9-passenger carry-all vehicle. The authorities concerned agreed to this proposal and also decided that, when sufficient information on the field-work was available, a meeting of a consultative board would be held to determine the future direction and scope of the Special Fund Project. The recommended additional personnel were subsequently recruited.

41. Mr. John Foster of Aero Service Corporation arrived on 10 December 1962 to act as a consultant on the use of the Geo Logger for electric and gamma-ray logging. During his 5-day stay he checked out the equipment, ran logs on selected wells and concurrently gave operating instructions to project personnel. Mr. Foster also served as a consultant from 16 to 21 February 1963.

42. As field-work neared completion in the fall of 1963, it was felt that the findings of the Special Fund study should be subjected to a critical independent review, particularly because they conflicted with the findings of earlier reports. For this purpose, the Bureau of Technical Assistance Operations engaged as a consultant Mr. Thad G. McLaughlin, Chief of the Rocky Mountain Area, Ground-Water Branch, United States Geological Survey. Mr. McLaughlin was considered particularly suitable because of his many years of experience with the hydrogeology of arid basins. He was in Jordan from 9 September until 12 October 1963 (except for a one-week period), during which time he examined previous reports on the Azraq area, the findings of the Special Fund team and hydrogeologic conditions in the field.

43. In 1963, Mr. McLaughlin submitted two reports on his findings to United Nations Headquarters. He emphasized the following points in his reports:

(a) Earlier reports on the Azraq Basin suggested that 5 to 20 per cent of the precipitation reaches the water-table and that the difference between the recharge within the basin and the discharge at El-Azraq represents the additional perennial supply available for development. Such percentages for recharge are much too high for most desert basins. For the purpose of comparison, the recharge of the high plains aquifers of the western United States has been determined to be 1 to 2 per cent of the precipitation. The recharge in a typical desert basin generally is less than 1 per cent of the precipitation. The geology of the Azraq Basin is such that above-average recharge is to be expected in the northern part, which is underlain by basalt, and below-average recharge is to be expected in the remainder of the basin, which is underlain by chalk and lake or playa deposits;

(b) Contours drawn on the water-table show that the shallow ground water moves from all directions towards the springs and marshes at Azraq; hence, the discharge at Azraq represents essentially the total perennial groundwater supply of the Azraq Basin;

(c) Speculation that the springs rise from great depths along fault planes is disproved by the fact that the temperature and chemical quality of the spring water are those of the shallow ground water;

(d) The discharge from the springs and marshes at Azraq represents between 1 and 2 per cent of the total estimated precipitation within the basin. The fact that this percentage of recharge is larger than for an average desert basin indicates that some recharge is derived from outside the basin. It may also reflect the relatively greater rate of recharge in the area of volcanics north of El-Azraq;

(e) The Kurnub sandstone lies at such great depth in the Azraq Basin that the cost of penetrating it with wells would be prohibitive under present or immediately foreseeable economic conditions;

(f) Significant quantities of ground water may be in storage in the rocks above the Kurnub sandstone, but the stratigraphy of the area, together with the results of pumping and bailer tests of many wells, suggest that permeabilities are so small that large-capacity wells generally cannot be developed in most places. Specific capacities (discharge in gallons per minute (gpm) per foot of drawdown) are almost all lower than is commonly found in areas of large-scale groundwater development;

(g) The depth to water in the rocks above the Kurnub sandstone increases generally outward from the centre of the basin with the result that initial pumping lifts in some areas can be expected to exceed 100 metres;

(h) The quality of the ground water in all the area, except that underlying the basalt, is of C 3 and C 4 class—according to United States Salinity Laboratory standards. The water is largely unsuitable for the irrigation of most soils in the Azraq Basin;

(i) The quality of the water beneath the basalt is generally in the C 2 class and would be suitable for irrigation of Azraq soils only with extensive leaching, treatment and drainage;

(j) Extensive development of ground water from the area beneath the basalt, if economically feasible, would reduce or deplete the flow of the springs at Azraq;

ject." It was Mr. Geraghty's opinion that it was premature to go into an engineering feasibility study at that time, but that it might be possible to accelerate certain phases of the current programme by the addition of more manpower and equipment. Accordingly, he recommended the recruitment of three more experts—a driller-tool-pusher, a geologist and an administrator; also, one additional pick-up truck and one 9-passenger carry-all vehicle. The authorities concerned agreed to this proposal and also decided that, when sufficient information on the field-work was available, a meeting of a consultative board would be held to determine the future direction and scope of the Special Fund Project. The recommended additional personnel were subsequently recruited.

41. Mr. John Foster of Aero Service Corporation arrived on 10 December 1962 to act as a consultant on the use of the Geo Logger for electric and gamma-ray logging. During his 5-day stay he checked out the equipment, ran logs on selected wells and concurrently gave operating instructions to project personnel. Mr. Foster also served as a consultant from 16 to 21 February 1963.

42. As field-work neared completion in the fall of 1963, it was felt that the findings of the Special Fund study should be subjected to a critical independent review, particularly because they conflicted with the findings of earlier reports. For this purpose, the Bureau of Technical Assistance Operations engaged as a consultant Mr. Thad G. McLaughlin, Chief of the Rocky Mountain Area, Ground-Water Branch, United States Geological Survey. Mr. McLaughlin was considered particularly suitable because of his many years of experience with the hydrogeology of arid basins. He was in Jordan from 9 September until 12 October 1963 (except for a one-week period), during which time he examined previous reports on the Azraq area, the findings of the Special Fund team and hydrogeologic conditions in the field.

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(b) Contours drawn on the water-table show that the shallow ground water moves from all directions towards the springs and marshes at Azraq; hence, the discharge at Azraq represents essentially the total perennial ground-water supply of the Azraq Basin;

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(h) The quality of the ground water in all the area, except that underlying the basalt, is of C 3 and C 4 class—according to United States Salinity Laboratory standards. The water is largely unsuitable for the irrigation of most soils in the Azraq Basin;

(i) The quality of the water beneath the basalt is generally in the C 2 class and would be suitable for irrigation of Azraq soils only with extensive leaching, treatment and drainage;

(j) Extensive development of ground water from the area beneath the basalt, if economically feasible, would reduce or deplete the flow of the springs at Azraq;

(k) Development of the shallow water near the springs would disturb the salt water-fresh water balance and would be likely to cause rapid deterioration of the quality of the spring water;

(l) To protect the fresh-water supply at El-Azraq, the drilling and equipping of wells for discharges of more than 10 gpm should not be permitted in the area around the springs and marshes. The area should perhaps extend outward from the springs and marshes to the points where the base of the shallow aquifer is at an elevation higher than the shallow water-level at Azraq—i.e. 510 metres.

(m) Pumping water from Azraq Springs at the present rate may not seriously upset the fresh water-salt water balance. There is a point, however, beyond which there probably would be damage;

(n) A chemical-quality monitoring programme should be established immediately to permit early detection of any deleterious effects of pumping water from the Azraq Springs.

44. Mr. McLaughlin gave his opinions at a board meeting on 7 October 1963, which was attended by members of the Jordanian Government, the Special Fund, the Bureau of Technical Assistance Operations and the Azraq Ground-water Project. It was agreed at the meeting that adverse soils and weather conditions and the lack of sufficient water for irrigation made large-scale economic development of the Azraq area unfeasible. Therefore, it was mutually decided that further deep-well drilling was not justified and that the Azraq Ground-water Project should be phased out within 6 to 8 months. The project manager presented a phase-out plan at the meeting, which was accepted with minor changes. After final approval of the plan by the Jordanian Government and the Special Fund, the phase-out proceeded according to schedule and was completed by May 1964.

F. Definitions of special terms

45. The definitions given below are of terms commonly used in ground-water reports. An interpretation of some of the Arabic words used on the maps and in the text of this report also are included.

46. The technical terms commonly used are:

(a) Advection: the exchange of energy or moisture due to horizontal heterogeneity in conditions at the earth's surface.

(b) Anion: a negatively charged ion in a solution of an electrolyte.

(c) Aquiclude: a formation, part of a formation, or a group of formations that is not capable of transmitting significant quantities of water.

(d) Aquifer: a formation, part of a formation, or a group of formations that will permit appreciable water to move through it under field conditions.

(e) Artesian pressure: mainly the same as hydrostatic pressure (see "Head").

(f) Cation: a positively charged ion in a solution of an electrolyte.

(g) Confined ground water: ground water that is under sufficient pressure to rise above its point of entry into a well bore, but which does not necessarily rise above the surface of the ground.

(h) Evapotranspiration: a term embracing that portion of the precipitation returned to the air through direct evaporation or by transpiration of vegetation, or by both, no attempt being made to distinguish between the two.

(i) Ground water: water in the zone of saturation below the land surface. It does not include downward percolating water, capillary fringe water and soil moisture, all of which constitute vadose water in the zone of aeration or unsaturated zone.

(j) Head (pressure head): hydrostatic pressure expressed as the height of a column of water that can be supported by the pressure. In this report the head is expressed in feet or metres above or below mean sea level.

(k) Isohyetal line: an isohyetal line, or an isohyet, is a line on a land or water surface, all points along which receive the same amount of precipitation.

(l) Permeability: a measure of the ease of flow of water through a formation. The coefficient of permeability is the rate of flow of water, in gallons per day (gpd), through a cross-section of 1 square foot under a unit hydraulic gradient at a temperature of 60° F. The field coefficient is not corrected for temperature and describes the flow at the prevailing water temperature.

(m) Piezometric surface: an imaginary surface that everywhere coincides with the static level of the water in the aquifer. It is the surface to which the water from a given aquifer will rise under its full head.

(n) Safe yield: the amount of water that can be withdrawn from a ground-water basin perennially without producing undesired results, such as excessive pumping lifts or deterioration of water quality. Any draft in excess of safe yield is overdraft, or mining of ground water.

(o) Storage coefficient: the volume of water released from storage in each vertical column of the aquifer having a base of 1 foot square when the water-table or other piezometric surface declines 1 foot.

(p) Surface water: any water, moving or not, on the surface of the land.

(q) Transmissibility coefficient: the rate of flow of water, in gallons per day at the prevailing temperature, through a vertical strip of the aquifer 1 foot wide having a height equal to the thickness of the aquifer and under a unit hydraulic gradient. The coefficient of transmissibility equals the coefficient of permeability times the height of the aquifer, in feet.

47. Some of the Arabic words used in the report are:

(a) *Ein:* a spring;

(b) *Jebel:* hill or mountain;

(c) *Qá:* a depressed plain, often characterized by mud or salt flats;

(d) *Qasr:* fort or castle;

(e) *Wadi:* a dry watercourse or valley.

Table 1

EQUIVALENT MEASURES

	Measure	*Equivalent*
Exchange		
	1 Jordanian dinar (JD)	1,000 fils
		1 £ Sterling
		$ US 2.80
Weight		
	1 kilogramme	2.2046 pounds avoirdupois
Length		
	1 metre	3.2808 feet
	1 foot	0.3048 metre
	1 kilometre	0.62137 mile
	1 inch	2.54 centimetres
Area		
	1 donum	1/10 hectare
		¼ acre (0.247 acre)
	1 acre	0.405 hectare
	1 square mile	259 hectares
	1 square kilometre	100 hectares
Volume		
	1 cubic metre	264.17 United States gallons
	1 United States gallon	0.83311 Imperial gallon
	1,230 cubic metres	1 acre-foot
Discharge		
	1 cubic metre per hour	4.40 United States gpm
		0.0195 acre-feet per day
	1 United States gpm	0.0631 litres per second

Note: The United States gallon is the gallon measurement used in this report.

I. GENERAL GEOLOGY

A. Summary of stratigraphy

48. The general geology of Jordan has been described by Ionides and Blake, Quennell, and Burdon.[1] These reports are the result of many years of study and should be referred to for information on the regional geology of Jordan. In the following discussion, emphasis is on the geologic formations that have the most influence on the ground-water resources of the Azraq Basin. The areal distribution of the lithological units is shown on map 2. Table 2 gives the provisional stratigraphy of the Azraq area. Additional data on the subsurface stratigraphy are given in the logs of wells.[2]

[1] See Introduction, footnotes 5, 2 and 3.

[2] See Annex I, Table 20; and also map 3 in pocket.

49. Pre-existing geological knowledge was supplemented during the Special Fund study by geological mapping on aerial photographs at a scale of 1:50,000. The photo-geological mapping was checked in the field, but in many places the lithological contacts were obscured by scree or by detritus and could not be traced accurately over long distances. Thus, many of the contacts are approximate and are shown by dashed lines on map 2.

50. Insufficient palaeontological data were available during the Special Fund study for dating formations and units; therefore, the stratigraphic sequence in this report is based on lithological characteristics. Subdivisions of the formations are based on descriptions by other authors and on well logs. Facies changes complicate the stratigraphy over much of the basin.

Table 2
PROVISIONAL STRATIGRAPHY OF THE AZRAQ BASIN

Era	*Period*	*Epoch*	*Series*		*General Lithologic Character*	
	Quaternary	Recent Pleistocene	Undiffer- entiated		Clay, silt, sand, and gravel	Basalt flows, dikes and beds of volcanic ash
		Pliocene Miocene	Plateau group		Sandstone, sandy limestone, marl	
		Oligocene	Emergence and planation			
Cenozoic	Tertiary	Eocene	Belqa Series	5	Chalk and marl.	
				4	Chalk, concretionary flint, chalky limestone, thick-bedded chert.	
		Palaeocene		3	Marl, thin-bedded chert and limestone, bituminous and phosphatic marl and shale.	
Mesozoic	Cretaceous	Danian		2	Limestone, thick-bedded chert, thin-bedded sandtsone and marl.	
		Senonian: Maestrichtian Campanian Santonian Coniacian		1	Marl and shale.	
		Turonian	Ajlun Series	7	Limestone, fossiliferous, often cavernous, concretionary chert.	
				6 & 5	Gray shale, limestone, and marl.	
		Cenomanian		4	Crystalline limestone, locally dolomitic, often honeycombed.	
				3	Gray shale with interbedded gray to black, hard limestone.	
				2 & 1	Dolomitic limestone interbedded with marl and shale.	
		Albian Aptian	Kurnub sandstone		Fine-grained, friable sandstone with some beds of shale, marl and limestone.	

Palaeontological studies are currently being done in Jordan by the Geological Survey Mission of the Federal Republic of Germany and others; such studies ultimately will make possible the dating of formations and units. In 1959, Hunting Technical Services Limited made stratigraphic correlations between the Azraq Basin and adjacent areas on a lithological basis.

51. The project area is underlain by a considerable thickness of sedimentary rocks that lie on granitic basement rocks of Pre-Cambrian age. These sedimentary formations were penetrated in well AZ-1, which ended in the upper Kurnub sandstone; and by Safra No. 1 well, which penetrated the entire sedimentary section and bottomed in the Pre-Cambrian basement rocks. The oldest sedimentary rocks exposed in the area are of Turonian age, but they crop out only in a small area on the north-western edge of the project area. Sedimentary rocks of Late Cretaceous age and of Tertiary age underlie the southern part of the area. The northern part of the basin is underlain by basalt flows of Miocene to Recent age. In some places, the older sedimentary rocks and the volcanics are mantled by scree and detritus or by recent alluvium in depressions and wadis.

52. The Kurnub sandstone, of Late Jurassic and Early Cretaceous age, does not crop out in the project area, but it is exposed in stream valleys west of the Azraq drainage basin. In the Zarqa River valley, where the formation overlies the Zarqa group, it has a thickness of about 200 metres and consists of poorly consolidated multi-coloured sandstone. In Safra No. 1 well, the formation contains interbedded shale and limestone in the upper part, with the percentage of sandstone increasing with depth. The base of the formation was not accurately defined in this well. The upper part of the Kurnub sandstone that was penetrated in well AZ-1 is interbedded with thin layers of shale and marl (see Annex I, Table 20).

53. Overlying the Kurnub sandstone is a series of limestones, marls and shales. These beds constitute the Ajlun Series of Cenomanian and Turonian age. They crop out over large areas along the east side of the River Jordan; but in the project area, only the upper part of the series is exposed in a small area near Qasr Hammam es-Sarhk. The formation is fossiliferous and consists mainly of hard limestone with interbedded marl and shale. Outcrops show a well-developed joint system in the limestone, and in some places a karst

topography has been partly developed on the surface. Some of the sink holes reach a depth of about 2 metres.

54. Blake gave a list of fossils for the Ajlun Series for different parts of Jordan[3] and Wolfart divided the formation into seven units for the Irbid area.[4] Masri described a complete section in the Amman-Zarqa area.[5] In other parts of Jordan lithologically similar beds have been given different names; so in order to avoid confusion, numbers only are used in this report to designate the units. The numbers correspond to those used by Hunting Technical Services Limited in the area adjoining the Azraq Basin in the west.[6] The seven units do not completely correlate with those used by Wolfart, and the units A 1-2 and A 5-6 are grouped together because separation without sufficient palaeontological determinations was difficult.

55. In the Azraq Basin, the lithological characteristics of the Ajlun Series are shown by the logs of wells Safra No. 1 and AZ-1 (table 20), both of which penetrated the complete section. The logs show a change of facies and thickness between the two wells for some units. The total thickness of the series increases from 511 metres in Safra No. 1 well to 636 metres in well AZ-1.

56. The Belqa Series of Late Cretaceous and Early Tertiary age overlies the Ajlun Series and crops out over much of the project area. The formation also crops out over a large part of the rest of Jordan. Quennell defined the series as all the marine sediments deposited in eastern Jordan from the end of the Turonian to the final emergence of the land in the Oligocene. Included in the formation are marls, chalks, limestones, chert, concretionary flint, and bituminous and phosphatic rocks. The formation was subdivided into five units on the basis of lithology, but the units were not named. These numbered units also correspond to the numbering system used by Hunting Technical Services Limited. Wolfart also numbered units of the Belqa Series, but his numbering system does not correlate exactly with the one used in this report.

57. At no place in the project area is a complete section of the Belqa series exposed in outcrop or included in a well log. Owing to facies changes in the formation, reference should be made to the logs of wells for a lithological description of the units at different places in the basin. The following brief description of the units is based on examinations of the few good exposures in the Azraq Basin and on the logs of wells. The regional lithological characteristics that are common to each unit are emphasized.

58. The B 1 unit is exposed only in a very small area near Qasr Hammam es-Sarhk and consists predominantly of soft marl with interbedded shale. The marl ranges in colour from white to pink and is chalky in some places.

59. The B 2 unit also is exposed only in a small area near Qasr Hammam es-Sarhk. The unit consists of interbedded crystalline limestone, gray to buff chalk, and thick beds of brown to black chert. In some places the beds of chert are fossiliferous and reach thicknesses of 1 to 2 metres. The limestone of the unit is interbedded with thin layers of calcareous sandstone and gray marl in well AZ-1.

60. The B 3 unit crops out along the western edge of the project area and consists of thick beds of gray marl interbedded with beds of shale and hard multicoloured limestone. Bituminous and phosphatic marl and shale, which were identified in gamma-ray and lithological logs of wells, form distinctive marker beds in the unit.[7] A bed of chalk concretions in the upper part of the unit also is prominent and can be traced over much of the outcrop area. The unit contains some thin beds of black chert.

61. Much of the western-central part of the basin is underlain by the B 4 unit. It is composed predominantly of white to cream-coloured chalk with beds of chalky limestone and brown chert. The chalk and limestone locally contain solution cavities and channels. Partial sections of the unit are exposed near Wadi Rajil immediately north of Tel Qarma and in the area between Qasr el-Kherane and Qasr Tuba. Concretionary flint and chert are diagnostic of this unit in most places.

62. The boundary between the B 4 and B 5 units is poorly defined in outcrops and in well logs. Poorly-bedded, white to cream-coloured chalk of the B 5 unit crop out on the sides of Edh Dhahkiye, a flat-topped hill near the border of Saudi Arabia. In wells AZ-10 and 14 the unit consists of marl; in well AZ-19 it contains marl with some limestone and chert.

63. The volcanic rocks of Miocene to Recent age that are exposed in the large area north of El-Azraq consist mainly of black, olivine basalt with a large content of augite. Beds of clay and volcanic ash intercalated with the basalt indicate at least two flows. The surface of the basalt flows is mantled in many places by sub-rounded boulders of basalt and in some places by local deposits of alluvium. The maximum thickness of the volcanics in the project area is not known, but 229 metres of basalt were penetrated in the Tapline 6-A well.

64. The eastern central part of the project area is

[3] G. S. Blake, and W. J. Goldschmidt, *Geology and Water Resources of Palestine* (Jerusalem, 1947), pp. 80 to 82.

[4] R. Wolfart, *Geology and Hydrology of the Irbid District, Hashemite Kingdom of Jordan* (Hannover, Fed. Rep. of Germany, Bundenanstalt für Bodenforchen, 1959).

[5] R. M. Masri, *Columnar and Geomorphic Columnar Section, Amman-Reseifa-Zarqa* (Amman, 1963).

[6] Hunting Technical Services Limited, "East Bank Jordan Water Resources, Report on Hydrogeology," Draft Report for Sir M. MacDonald and Partners and the Hashemite Kingdom of Jordan (Boreham Wood, 1964).

[7] See Figures XIV and XV in pocket and also Annex I, Table 20.

underlain by the Plateau Group of Pliocene and Miocene age. No complete sections of the group have been measured in the Azraq Basin, but it crops out in the hills of Tel Qarma and Edh Dhahkiye and in some wadies. In outcrop, it consists of hard to friable sandstone interbedded with sandy limestone; in some places marl is included. The maximum thickness of the group in the Azraq Basin is not known.

65. Recent unconsolidated deposits in the area include residuum that covers much of the land surface, slope wash and alluvial fans, and alluvium that partly fills the playas and wadies. Although these deposits mantle the consolidated rocks in many places, the areal distribution of only the principal playa deposits are shown on map 2. The alluvial fills in the wadies are not shown because, in general, they are not thick and are not important water-bearing formations. Clay, sand and gravel comprise the deposits in the wadies; the deposits that form the playas are mostly clay and silt. The alluvium that underlies Qá el-Azraq contains gypsum and other evaporites. Mining of the saline evaporites supports a local salt-production industry at El-Azraq.

B. Geological history

66. The following discussion of the geological history, structure and volcanism of eastern Jordan is based largely on the reports of Picard, Quennell and Burdon,[8] and in part on field observations made during the Special Fund study.

67. The interval of geological time from the Cambrian period to the Middle Cretaceous period was marked by almost continuous deposition of terrestrial sandstones with only occasional limited transgressions of the sea from the north or north-west. In the Cenomanian time, a major transgression occurred and the sea flooded over almost all of Jordan. From then until the Upper Eocene time, except for limited withdrawals and a change in the nature of the sediments, the sea covered the greater part of the region. These transgressions and regressions are represented in the Azraq Basin by the changes of facies in the Ajlun and Belqa Series that are found in some well bores and outcrops.

68. During the Eocene time, the sea withdrew and the deposition of terrestrial sediments started again. The exact time at which the seas finally withdrew from eastern Jordan is difficult to determine because many of the late marine rocks were removed by erosion after emergence. According to Burdon, eastern Jordan was land throughout the Upper Oligocene time and into the Lower Miocene; during this period, erosion produced a peneplain.[9] In the Lower Miocene time, tectonic activity commenced and thereafter almost all sediments were of terrestrial or lacustrine origin.

69. The plateau basalt flows were erupted at intervals over the period from the Middle Miocene to the Historical. The flows were extruded along north-westerly and south-westerly trending tension fissures and they covered large areas of southern Syria and northern Jordan.

70. The Neogene undifferentiated deposits were formed in lakes or on land when erosion commenced after the rejuvenation of the Oligocene peneplain by uplift and tectonics during the Middle Miocene time.

C. Structure and volcanism

71. The geologic structure of Jordan shows the effects of two main periods of deformation. The first, which took place in Late Mesozoic and Early Tertiary time, consisted of gentle warping and folding of the rocks. Some of these folds began forming in Late Cretaceous time while much of Jordan was submerged and, as ridges on the bottom of the sea, they caused local variations in the thickness and lithology of sediments deposited contemporaneously.

72. Superimposed on these simple folds are faults associated with the Dead Sea Rift valley. These faults originated in the Late Tertiary and the Pleistocene times and consist essentially of the great north-trending faults along which the Rift valley has developed; related faults, most of which strike north-west; and sharp monoclinical flexures. The basalt extrusive rocks are closely associated with these structures.

73. In the project area, it was not possible to determine the attitude of the Belqa Series in many places. Therefore, the dips of the bedding planes in the B 4 unit provided most of the surface data on structure. Map 2 shows that most of the dips that could be measured are of small magnitude. The axes of the anticlines and synclines shown on this map trend in a north-westerly direction and roughly parallel the faults. A sharp downwarping of the bedding along the north-eastern edge of Wadi el-Harth was observed in the field. Such a monoclinical flexure may be the surface expression of faulting at depth.

74. Field examination of the fault that begins at Tel Qarma indicates that the vertical displacement in the immediate vicinity of Tel Qarma is about 300 metres. Aerial photos show that this fault apparently dies out and is cut by minor cross-faulting in a north-westerly direction, but these minor features are not shown on the geological map. Field examination of the other fault immediately north of Wadi el-Janab indicates that the vertical displacement here is on the order of 60 to 100 metres.

75. The dikes in the north-eastern part of the project area (see map 2) show clearly on aerial photographs and are oriented in a north-western and south-

[8] L. Picard, "Structure and Evolution of Palestine, With Comparative Notes on Neighbouring Countries", *Bulletin of the Geological Department of Hebrew University*, Jerusalem, Nos. 2, 3 and 4 (1943); Quennell, op. cit.; Burdon, op. cit.

[9] Burdon, *ibid.*, p. 3.

western direction as are the faults. The similarity in orientation indicates that the dike material and probably most of the basalt flows were extruded through pre-existing faults. Interflow beds of clay and volcanic ash indicate at least 2 separate basalt flows in the area; probably there are more.

II. HYDROLOGY

A. The hydrologic cycle

76. The ultimate source of all water in the Azraq Basin is precipitation. Part of the rain is carried off to playas by the intermittent streams, part evaporates and the remainder infiltrates the ground. The water that is not consumed by vegetation or held by molecular attraction moves downward and is added to the zone of saturation in the soil or rocks. Water in the zone of saturation percolates laterally through the more permeable consolidated rock formations downgradient toward the topographically low centre of the basin. Some recharge is contributed by deep underflow through consolidated rocks that have outcrops areas outside the Azraq drainage divide. Ground water is discharged naturally from the project area through springs and seeps, by evapotranspiration, possibly by deep subsurface outflow and artificially from wells. In general, during a long period of years, if ground water is not depleted by overpumping, the quantity of discharge is equal to the quantity of recharge. The hydrologic cycle for the wet season is illustrated in figure I. The simpler dry-season cycle is illustrated in figure II, which shows that essentially all of the water perennially available is ground water and that the principal mechanism for natural discharge of water from the basin is evapotranspiration.

B. Shape and slope of the water-table

77. The regional water-table in the area is defined by water-levels in wells tapping unconfined (water-table) aquifers. A water-table contour map (figure XIX) was prepared from records of water-level measurements made in 22 wells during this investigation.[1] The contour lines pass through points of equal elevation on the water-table and show its position and configuration at the time the measurements were made. In general, the direction of ground-water movement is downgradient at right angles to the contour lines. The water moves from areas of recharge to points or areas of discharge; in the report area, the area of discharge is El-Azraq. The gradient of the water-table is governed by the rate of flow of the ground water and by the thickness and permeability of the rock materials through which the water moves. Irregularities in the shape and slope of the water-table may be caused by local differences in gain or loss to the ground-water reservoirs or by differences in the thickness and permeability of the rock materials. The configuration of the water-table conforms roughly to the configuration of the land surface. In the report area the movement of ground water is inward from the surrounding topographic divides toward the central low area at Qá el-Azraq.

[1] See map 4 in pocket.

78. Not enough data were available to construct contours on the piezometric surfaces of the confined ground-water bodies in the basin. The few wells in which the ground water is under artesian pressure are described in chapters IV and V and in table 20. Only in wells AZ-1 and AZ-13 was the water under sufficient pressure to flow at the land surface.

C. Recharge

79. Direct infiltration of rainfall is generally an important source of ground-water recharge in humid and subhumid climatic zones. In arid zones, however, the situation usually is quite different. According to studies made by Cronin, Theis and others, recharge by direct infiltration is negligible in arid regions.[2] Aside from sandy deserts and outcrops of permeable rocks, such as fractured limestone or basalt, the land surface in such regions has a low infiltration capacity, depth to the water-table is usually great and the amount of rain that falls during any one storm is often so small that even with moderate infiltration capacity the depth to which the precipitation can satisfy specific retention will be less than a metre. As a hypothetical case consider a rainfall of 10 millimetres on a horizontal surface with a 10 per cent sedimentary grade size of 0.125 millimetres (border line between fine sand and sandy clay). The porosity is 44 per cent, specific yield is 13 per cent and specific retention is 31 per cent.[3] Assume that conditions are such that there is no runoff and that soil moisture in the upper portion of the profile is zero. Then 10 millimetres of rain will saturate 22.6 millimetres of soil and of this water, 31/44 (70 per cent) is restrained by molecular attraction. This leaves only 3.0 millimetres for infiltration to greater depths and it may be calculated that by the time infiltration has penetrated to a depth of 32.4 millimetres the entire quantity of water is restrained from further

[2] J. G. Cronin, *A Summary of the Occurrence and Development of Ground Water in the Southern High Plains of Texas*, United States Geological Survey Water-Supply Paper 1963 (Washington, D.C., 1964).

[3] American Society of Civil Engineers, Committee on Hydrology of the Hydraulics Division, *Hydrology Handbook* (New York, 1949).

Figure I Hydrologic cycle of the Azraq Basin, wet season

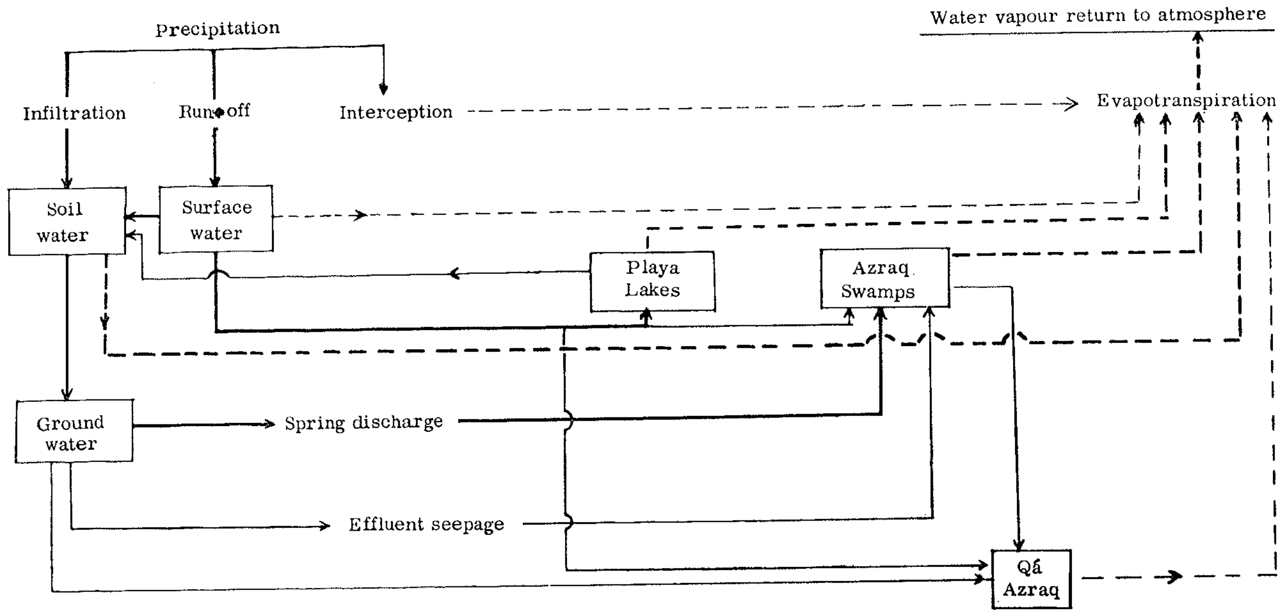
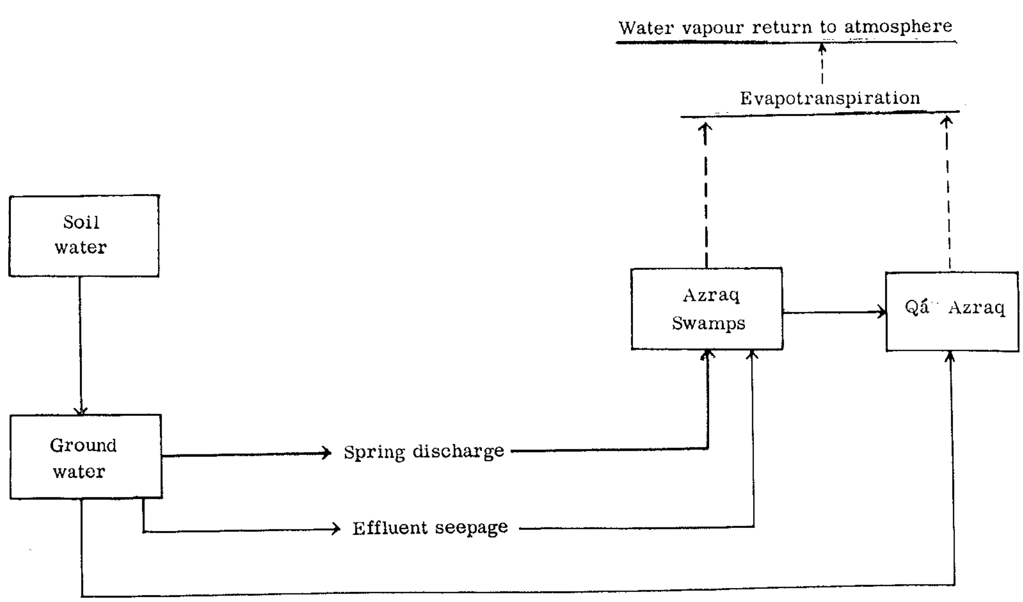


Figure II Hydrologic cycle of the Azraq Basin, dry season



downward movement. Drying of the soil to this depth will take place quite rapidly. The above example illustrates conditions that prevail in such arid regions as the Azraq Basin.

1. *Precipitation*

80. By most standard classifications of climate, the Azraq Basin is a desert region. According to Köppen's classification, the entire area is climatic type BWh, a hot desert climate, with the possibility that small areas on the western edge and in Syria are type BSh, a hot steppe climate. Burdon's report includes a precipitation map, which shows the isohyetal zones for Jordan, indicating that the project area has an arid climate. The map of eastern hemisphere arid homoclimates prepared by Meigs[4] is based upon the use of the moisture index as proposed by Thornthwaite.[3] Although the scale is too small for the map to provide more than a general indication, it does show the area as arid (UNESCO categories Ac13 and Ac23), again with the possibility that the western edge falls in the Sc13 semi-arid category.

81. A weather-station was established at the base camp to provide the data necessary for estimates of precipitation and evapotranspiration, and for comparison with other stations in the region. Instrumentation provided was as follows:

(a) Maximum-minimum thermometer;
(b) Wet- and dry-bulb thermometer;
(c) Aneroid barometer;
(d) Anemometer;
(e) Recording rain-gauge;
(f) Non-recording rain-gauge;
(g) Class A evaporation pan;
(h) Gunn-Bellani radiation integrator.

Data obtained are summarized in table 3. Radiation data are not included because the suppliers of the Gunn-Bellani could not furnish proper calibration data for the instrument and there were no facilities for making such a calibration locally.

Table 3

WEATHER DATA FOR THE AZRAQ BASE CAMP, 1962-1964

Year and Month	Mean Temp.	Maximum Temp.	Minimum Temp.	Average relative humidity 0800 hrs	Rain-fall	Evapor-ation[a]	Average wind velocity
	(degrees centigrade)			(percentage)	(millimetres)		(km/hr)
1962							
Nov.	—	—	—	—	0	—	—
Dec.	—	—	—	—	1.4	—	—
1963							
Jan.	—	—	—	—	7.5	—	—
Feb.	—	—	—	—	23.3	—	—
Mar.	14.0	28.5	1.0	—	0.4	245	—
Apr.	19.3	36.0	8.5	54	20.1	340	—
May	22.1	38.5	9.5	46	4.1	382	13.3
June	26.7	42.0	14.5	39	0	—[b]	14.2
July	28.5	40.0	18.5	43	0	540	16.1
Aug.	29.2	42.0	17.0	43	0	537	15.8
Sept.	26.5	41.0	16.5	48	Trace	392	12.2
Oct.	24.2	39.0	8.5	45	0.8	306	8.5
Nov.	17.0	29.0	2.0	54	0.2	173	5.7
Dec.	10.5	26.5	−5.5	68	29.9	102	6.8
1964							
Jan.	6.6	16.5	−6.0	70	12.1	79	8.5
Feb.	11.1	25.5	0.5	—	4.4	137	11.9

[a] United States Weather Bureau Class A Pan.
[b] Data questionable.

82. The highest temperature recorded was 42°C on 29 June and on 20 August 1963, while the minimum was -6°C on 21 January 1964. The mean annual temperature for the period from March 1963 to February 1964 was 19.6°C. Seven days of frost were recorded during December 1963 and nine days during January 1964. Maximum rainfall recorded in any essentially continuous storm was 17.7 millimetres during 10-11 February 1963. Winds are relatively steady during the summer, but in the winter they tend to be gusty, with wide variations from day to day. Although the average wind velocity in January 1964 was only 8.5 kilometres per hour (km/hr), the average for 18 January was 27.0 kilometres per hour, the second highest recorded for any 24-hour period. The anemometer was not equipped for instantaneous readings, but it is estimated that the peak velocity was in the range of 60-70 kilometres per hour. Pan evaporation for the year of record

[4] P. Meigs, "World Distribution of Arid and Semi-arid homoclimates", paper prepared for the United Nations Educational, Scientific and Cultural Organization Symposium on Arid Zone Hydrology, held in Ankara (Paris, 1953).

amounted to 3,633 millimetres (assuming 400 millimetres for June 1963), which, with a pan coefficient of 0.54 (see paras 97-122), gives an annual open-water evaporation of 1,950 millimetres.

83. Recharge in the Azraq Basin occurs in the winter during the rainy season. Precipitation in summer, falling on the sun-baked land surface at a period of high evapotranspiration, probably contributes little or nothing to ground-water replenishment. In his report on recharge in the Negev, where climatic conditions are similar to those in the Azraq Basin, Goldschmidt states: "It may be concluded . . . that underground water which occurs in regions with an annual rainfall of 100 millimetres and less is replenished only by water flowing in the natural drainage channels or by water accumulated in depressions . . . Replenishment by precipitation percolating into the aquifer does not occur . . . except perhaps through very porous soil and, very occasionally, after exceptionally heavy and extended rainfalls."[5]

84. The conclusions of Goldschmidt and other authors are applicable to the Azraq Basin, with the exception of the basalt shield where recharge is greater. The rain-storm on 10-11 February 1963 averaged only about 20 millimetres over the basin, and the intensity was only in the range of 1 to 2 millimetres per hour (figure III). Yet the run-off was sufficient to create playa lakes totalling at least 100 square kilometres in area. Test pits dug in the soil in the vicinity of the Azraq Base Camp immediately after the storm showed a depth of infiltration that ranged between 5 and 10 centimetres only.

85. This storm, however, probably did contribute to recharge because flash floods were widespread. The ability of the wadi beds to accept infiltration is variable. The lower reaches of even such major basins as Wadi al-Butm offer little recharge potential because the broad channel bed is silt-covered. Reaches where the channel width is restricted seem to offer the best recharge potential. In these reaches the floods have sufficient competence to move gravel and to scour out deposits of silt left by former floods. Good examples of such recharge areas are the narrower reaches of Wadi Meshash, Wadi Medeisisat and Wadi er-Ratam (see map 2). The flood in Wadi er-Ratam on 12 February 1963 reached a peak discharge estimated at 16 to 18 cubic metres per second. This apparently was unusual, because the local residents reported that this was the first time in their memory that the channel was filled from bank to bank. The recharge effect of this flood is illustrated by the hydrograph of the water level in well S-12 (figure IV). This well also exhibits a normal ground-water recession curve, which is absent in the hydrograph for well PAB-11. The latter hydrograph shows a small recharge response to rainfall which generally indicates low permeability and poor recharge characteristics for that particular area.

86. Water stored in the playa lakes, which form on the mud flats in the northern central part of the basin and along the south-west edge of the basalts, contributes little or nothing to ground-water recharge because the silt and clay mat of the playa surface is practically impermeable. A playa lake formed on a small mud flat north-east of the base camp on 11 February 1963. Although its area decreased gradually through evaporation, the lake still was an estimated 90 per cent of its original size on 5 March, on which date a test pit was dug at the water's edge. The pit penetrated a layer of silt-clay 49 centimetres in thickness, and it was found that after continuous water cover for 22 days the depth of infiltration was only 25 centimetres, a rate of less than 1 centimetre per day. More conclusive was the investigation made on 30 April at Qa'Khanna, 25 kilometres north-west of the Azraq police-post. A test pit was dug where the playa bed was still covered with a few millimetres of free water; the water was excluded from the pit by means of dikes. The silty clay had been covered continuously with water for 78 days at this time, yet total infiltration amounted to only 55 centimetres. The evidence indicates that the mud flats are ineffective as areas of ground-water recharge in the project area. Indications are that the principal area of ground-water recharge in the basin is the basalt shield. This assumption has been further demonstrated on the basis of water chemistry in chapter V (see paras 189-190).

87. In order to estimate the percentage of recharge over the basin, average precipitation was computed by Thiessen analysis (table 4). The value of 84 millimetres gives a total volume of 1.08×10^9 cubic metres of rainfall annually; ground-water discharge was estimated to be 2.08×10^7 cubic metres annually, or 2,385 m^3 per hour (see paras 124-126). Thus, the over-all recharge amounts to about 2 per cent of precipitation.

2. *Surface water and artificial recharge*

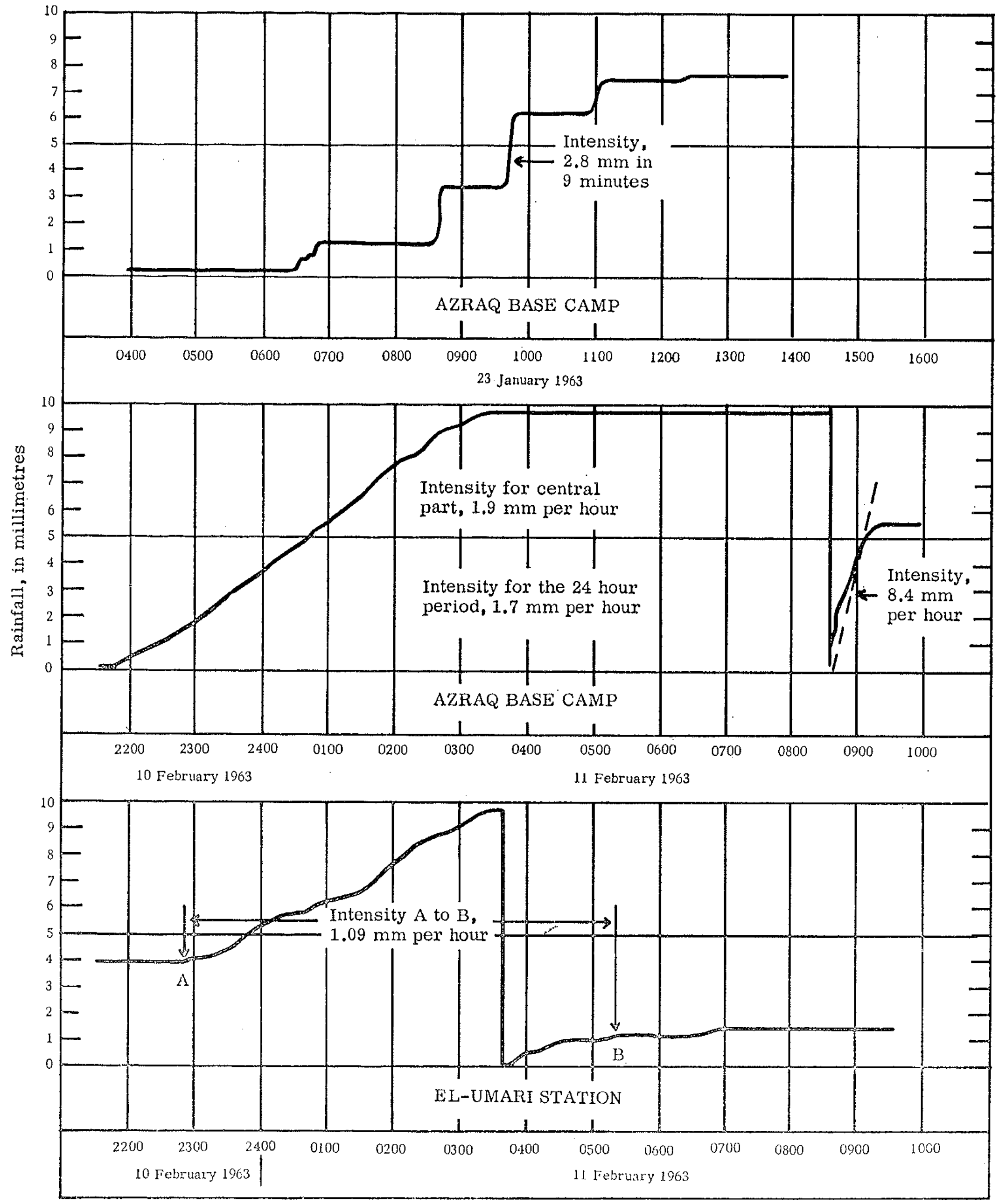
88. Data on surface-water run-off were not collected during this study, owing to the scarcity of suitable stream-gauging sites, the highly irregular patterns and frequency of flood-producing storms, and access difficulties. These factors combined would have made the cost and time involved in developing even preliminary information outweigh the benefits.

89. No effective methods for utilization of flood waters in the basin have been devised. Millions of cubic metres of water are lost by evaporation from the playa lakes, yet no practical answer seems apparent. Conventional surface reservoirs offer no immediate solution. Aside from the lack (so far as is known) of suitable sites, the great irregularity of the floods would make it impracticable to connect a municipal or irrigation supply to such an undependable source. Also, the life of such a structure would be greatly reduced by silting.

90. Installation of artificial recharge wells in the

[5] M. J. Goldschmidt, *On the Mechanism of the Replenishment of Aquifers in the Negev* (Ghent, International Association of Scientific Hydrology, 1961), Pub. No. 57, pp. 547 to 550.

Figure III Hydrographs of rainfall intensities

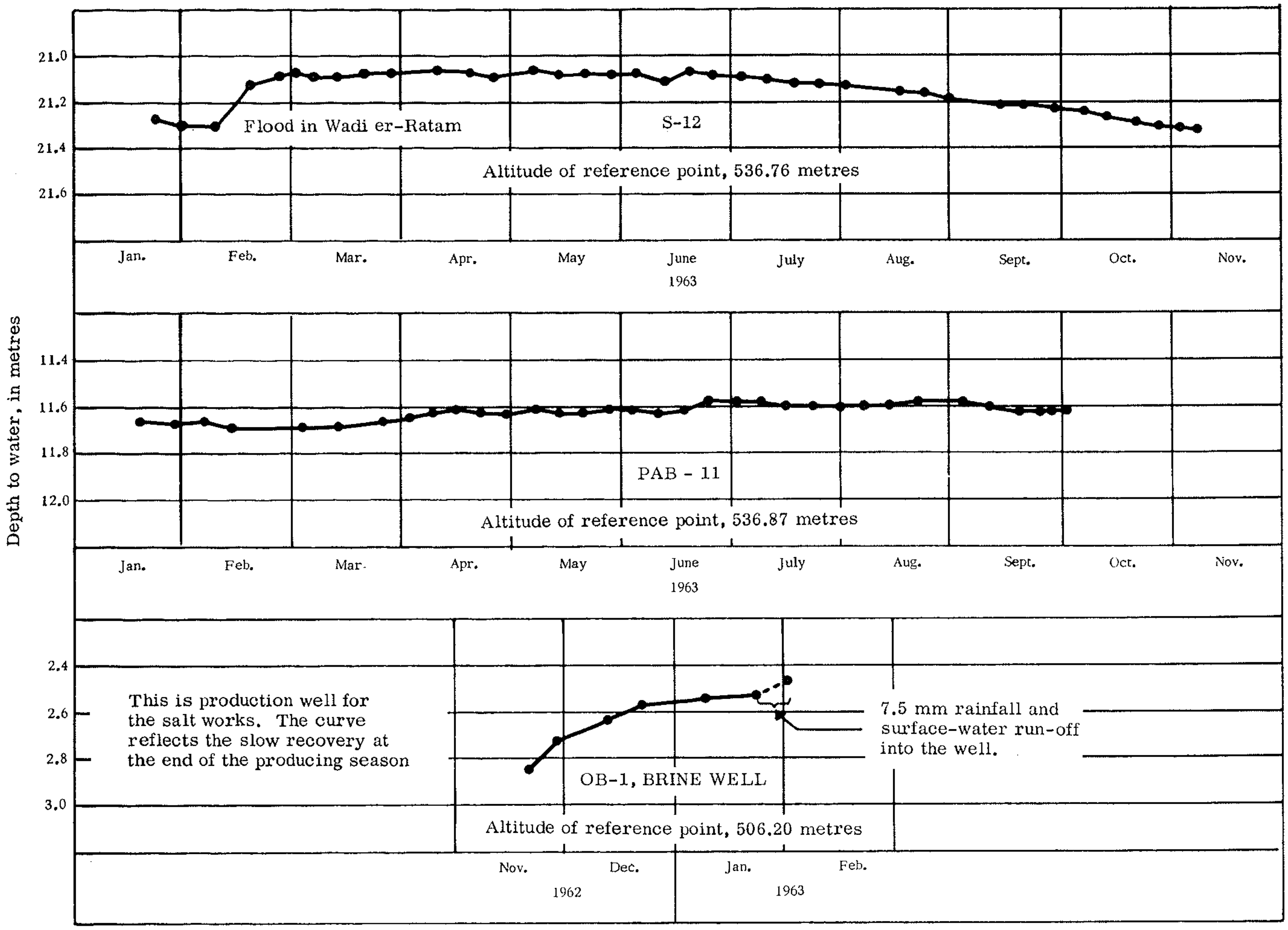


playas has been suggested frequently. Successful artificial recharge, whether by wells or by water-spreading, depends on recharge water that is essentially silt-free.[6] During flash floods in the Azraq basin, so much of the silt load going into the lakes is of colloidal or semi-colloidal size that even after several months the lake water is still a dirty brown, the wavelet motion alone being sufficient to maintain the material in suspension. Such water, if introduced into a recharge well without being settled first, probably would seal the well in a short time. The water-spreading schemes currently in use in the basin actually seem detrimental to ground-water recharge. Water that would ultimately arrive at wadi reaches where recharge can occur is instead blocked by dikes, where the silt load is dropped and the water remains to be lost by evapotranspiration.

91. Some consideration was given to the suggestion of cutting a trench across the north-western drainage divide near Qasr Hamman es-Sarkh, thus permitting the surface flow in that area to escape westward towards the Jordan River via Wadi Dhuleil, on which a reservoir is planned. This does not appear to be feasible owing to the cost of excavation that would be involved and to the problem of silting. The necessary

[6] R. K. Linsley, Jr., M. A. Kohler and G. L. H. Paulhaus, *Hydrology for Engineers* (New York, McGraw-Hill, 1958), p. 144.

Figure IV Hydrographs of observation wells



ditching would expose much of the silt already deposited in the flats to renewed erosion and to further transportation into Wadi Dhuleil. Because the volume of silt thus available probably would amount to millions of cubic metres, possibly a single flood could seriously shorten the useful life of a reservoir on the Wadi Dhuleil.

3. *Subsurface inflow*

92. Part of the recharge to the Azraq Basin may be by deep underflow beneath the western drainage divide. The Kurnub sandstone, the Ajlun Series and the Belqa Series crop out in the area between the Jordan River and the western boundary on the project area, which provides a catchment area for recharge.

Table 4

THIESSEN ANALYSIS OF PRECIPITATION FOR THE AZRAQ BASIN 1952-53 THROUGH 1961-62

Station	*Thiessen area (square kilometres)*	*Percentage of total area*	*Average precipitation (millimetres)*		*Weighted precipitation (millimetres)*
Salkad, Syria	478	3.7	218		8.1
Um el-Quttein	1,280	10.0	165		16.5
H-5	3,740	29.1	55		16.0
Azraq	4,672	36.5	48		17.5
Zarqa	204	1.6	114		1.8
Muwaqqar	1,201	9.4	163		15.3
Qatrana	1,032	8.1	100		8.1
Bayir	207	1.6	38		0.6
Total	12,814	100.0	Rounded to	84	83.9

The formations dip eastward under the Azraq Basin.[7] According to Brown Engineers International, test drilling indicated that both the Kurnub sandstone and the Ajlun Series have relatively good aquifer qualities in the Amman-Wadi Zarqa area.[8] In wells AZ-2 and Hamman No. 2, the Belqa Series was water-bearing; the Kurnub sandstone was reported to be water-bearing at a depth of 914 metres in Safra No. 1 well (map 2 and table 20). In well AZ-1 at El-Azraq, water under artesian pressure was found in the Kurnub sandstone and the Belqa Series.

D. Discharge

1. *Springs at El-Azraq*

93. The springs of El-Azraq, those of both Sheshan and Druze, rise from the bottom of four principal pools, which are shown on map 3 and, schematically, in figure V. These in turn discharge into channels and thence to the swamp areas. The free-water areas of the swamps expand and contract in accordance with the total energy, both radiant and advective, that is available for evapotranspiration, but there is little or no change in size of the vegetated area. The actual change of the free-water area can be witnessed day by day beginning in late September or early October, although this is a period when the discharges of the springs are decreasing.

94. Both surface and subsurface regimes were changed in 1956 when the Baker-Harza Canal was constructed from Ein Soda to a low point about 2.5 kilometres to the south. The purpose was to permit a controlled lowering of the pool level with a consequent reduction of back-head on the springs. The water-level of the pool was then controlled by flash-boards at the pool outlet. During excavation of the canal a number of smaller springs were developed. Three of these springs still flow into the canal, which also receives an appreciable amount of water from effluent seepage.

95. Spring discharges were gauged daily from November 1962 through March 1964 by Cipolletti weirs; the ones on Ein Qasiyah and Ein Soda had lengths of 150 centimetres and the others had lengths of 100 centimetres. The weir locations were the same as those used by Baker-Harza during their investigation except for the weir on the Baker-Harza Canal, which was relocated at the end of January 1963. Previously it had been used to gauge the combined flow of the A and B springs, but the location was unsatisfactory owing to constant erosion of the abutments and inadequate end contractions. The new location had the added advantage of gauging not only A, B and C springs but also the appreciable effluent seepage into the canal. Essentially all surface flow was accounted for by these weirs. The quantity of additional ungauged water that is discharged to the swamps from seepage that does not enter the canal and from other small, subsurface springs is not large and was estimated.

96. Discharge data are summarized in figure VI and in table 5. For Sheshan Springs, less discharge was recorded for about six weeks following the raising of the weir crests, which was done to provide proper aeration of the nappes. This was the time required to bring the pond levels up to the new equilibrium level. Response to the 1962-1963 winter rains is also evident. Prior to the rains, the total discharge (not including flow in the Baker-Harza Canal) had stabilized at about 1,400 m^3 per hour; the average for April 1963 was 1,500 m^3 per hour; an increase of 7 per cent. All the pools exhibit the effect of surface water run-off immediately following individual storms. The effect is of longer duration in the Druze group of pools, where the topography permits more prolonged run-off.

2. *Evapotranspiration*

97. The total inflow of water at El Azraq was estimated by assuming that all the water from the shallow aquifers is ultimately discharged by evapotranspiration, and by determining the evapotranspirative area and the rate of loss to the atmosphere for the same period.

98. Thornthwaite and Mather define evapotranspiration as: "the amount of water which will be lost from a surface completely covered with vegetation if there is sufficient water in the soil at all times for the use of the vegetation."[9] Penman presents a formula that contains variables, such as albedo, which are independent of climatic conditions.[10] Hence, the results obtained by the Thornthwaite and Penman methods would not necessarily be the same, even if both methods were theoretically perfect and were applied to identical climatic conditions.

99. The period of the year chosen for analysis was April, because the aerial photographs used for the determination of swamp areas were taken during late April and early May 1962. The required climatic data for 1962 were not available, so those recorded at the base-camp weather-station in 1963 were used. Application of the 1963 data to conditions in 1962 should cause no serious error, because most of the elements involved are conservative. One exception, which may have led to high results in the Penman method, is wind velocity.

100. Swamp areas were determined by planimetry of aerial photographs at a scale of 1:50,000. The various types of surfaces are practically indistinguishable at this scale and division of the types was made by

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[7] Quennell, op. cit.; Burdon, op cit.; and figure XIV of this report, in pocket.

[8] Brown Engineers International, Inc., *City of Amman, Final Engineering Report on the Water Distribution System*, report to the Hashemite Kingdom of Jordan (1960).

[9] C. W. Thornthwaite and J. R. Mather, "The Water Balance", *Publications in Climatology*, vol. VII, No. 1 (Centerton, New Jersey, Laboratory of Climatology, 1955).

[10] H. L. Penman, "Evaporation in Nature", *Physical Society London Reports on Progress in Physics*, vol. II, pp. 366-388, 1946-1947.

Table 5

MONTHLY AVERAGES OF SPRING DISCHARGES
(CUBIC METRES PER HOUR)

Month	*Ein Soda*	*Ein Qasiyah*	*Baker-Harza Canal*	*Druze North*	*Druze South*	*Total*
			1962			
Nov.	575[a]	547	—	215	52	1,579[c]
Dec.	589	544	—	217	48	1,588[c]
			1963			
Jan.	602	535	192	225	47	1,601
Feb.	619	560	197	240[a]	70	1,686
Mar.	625	560	196	233	64	1,678
Apr.	625	559	195	253	63	1,695
May	627	541	194	245[a]	59	1,666
June	614	535	180	215	53	1,597
July	598	525	172	225	50	1,570
Aug.	539	523	176	222	56	1,516
Sept.	515	510	170	245	57	1,497
Oct.	513	510	181	[b]	58	—
Nov.	514	515	180	—	60	—
Dec.	521	525	180	—	65	—
			1964			
Jan.	520	530	180	—	62	—
Feb.	523	530	180	—	62	—
					Average	1,600

Estimated, staff gauge displaced part of month.
[b] Pumping to Irbid commenced in September 1963.
[c] Assuming 190^3/hr in Baker-Harza Canal.

surface reconnaissance. The areas included in the planimetry were all those of low albedo. This includes all that show as black or dark grey; the dark grey areas are wet soil that is more or less saturated. The areas thus determined were, in square kilometres: (a) main Sheshan swamp, 5.66; (b) Baker-Harza swamp, 1.78; and (c) Druze swamp, 1.84. Thus, the total area was 9.28.

101. The Thornthwaite formula for potential evapotranspiration (ETP) is:

$$ETP — 1.6\ (10\ T_a/I)^a$$

in which I is a complex factor called the heat index, a is a cubic function of I, and T_a is the mean temperature. Thornthwaite and his associates prepared tables for the calculation of both potential evapotranspiration and the water-balance for different climatic conditions. Calculations used in this report are based upon the tables prepared by Thornthwaite and Maher in 1957.[11] This method must be adjusted when applied to the climatic conditions of such areas as Azraq. Wallen concludes that, in general, the evapotranspiration thus calculated will be 30 per cent too low and quotes Stanhill to the same effect.[12] A map of mean annual potential evapotranspiration, based upon the method of Thornthwaite, Maher and Carter gives an evapotranspiration of only 1,140 millimetres per year for the central Azraq area.[13] Assuming that this value is 30 per cent too low, then the corrected value is 1,630 millimetres per year, which more nearly approaches the following computed and adjusted values.

102. For this discussion, the mean temperature used was 21.6°C, which was recorded at the Azraq base camp (latitude 31° 50′ N) for the last half of April 1963. The values obtained for this temperature were:

(a) Heat index: I — 100;
(b) Unadjusted daily ETP: 3.2 millimetres;
(c) Adjusted daily ETP: 4.6 millimetres.

By applying the adjusted value to the planimetered swamp areas, the following discharges (given in m^3/hr) were obtained:

Main Sheshan swamp:	755	and	1,085
Baker-Harza swamp:	240	and	340
Total Sheshan	995		1,425
Druze swamp	245		350
Total Azraq	1,240		1,775

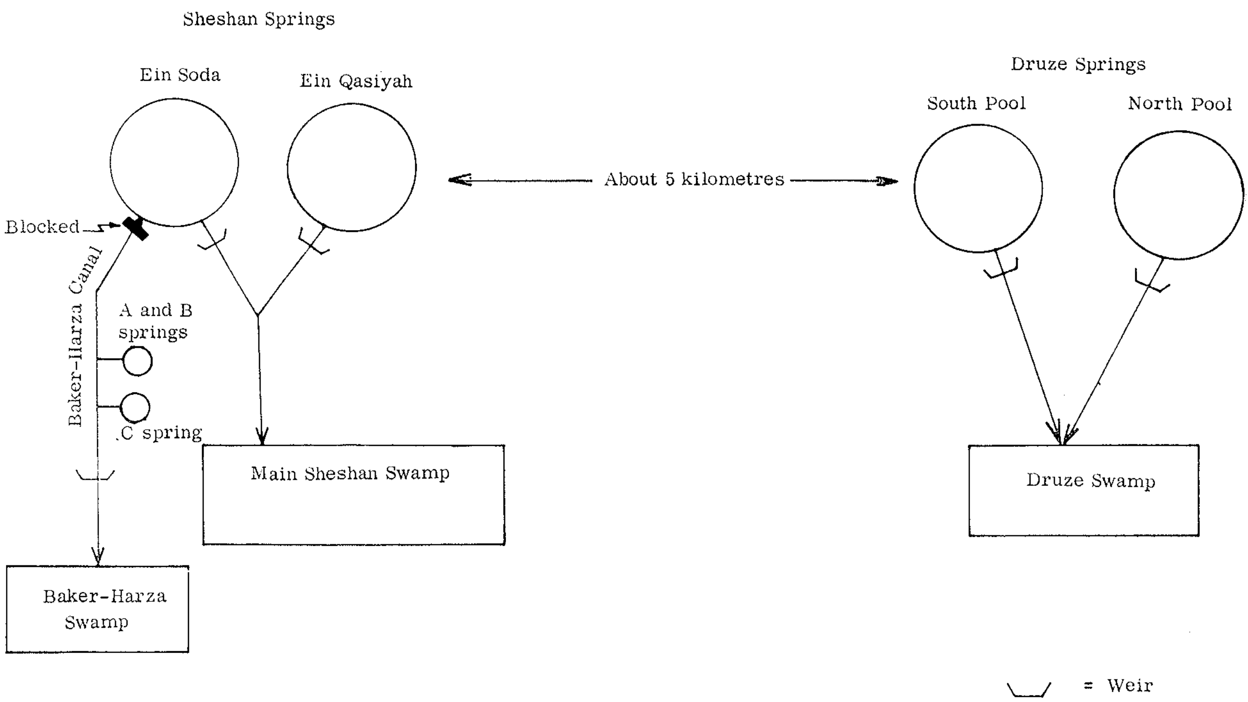
The figures in the first column were calculated directly while those in the second column were corrected by applying the adjusted daily evapotranspiration of 4.6 millimetres on the assumption that the Thornthwaite formula gives results that are 30 per cent too low. The

[11] C. W. Thornthwaite and J. R. Mather, "Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance", *Publications in Climatology*, vol. X, No. 3 (Centerton, New Jersey, Laboratory of Climatology, 1957).

[12] C. C. Wallen and G. Perrin de Brichambaut, *A Study of Agroclimatology in Semi-Arid and Arid Zones of the Near East*, FAO/UNESCO/WMO Inter-Agency Project on Agroclimatology (Rome, 1962); G. Stanhill, "The Accuracy of Meteorological Estimates of Evapotranspiration in Arid Climates", *Journal of the Institute of Water Engineers*, vol. 15, No. 7 (1962).

[13] C. W. Thornthwaite, J. R. Mather, and D. B. Carter, "Three Water Balance Maps of Southeast Asia", *Publications in Climatology*, vol. XI, No. 1 (Centerton, New Jersey, Laboratory of Climatology, 1958).

Figure V Schematic diagram of the Azraq Springs and Swamps



uncorrected values are too low, since they are less than those actually gauged at the weirs. Furthermore, the differences are too great to be explained by any reasonable error in either planimetrical or mean temperature. The corrected values give a total that corresponds reasonably well with the gauged discharge for April. Even if the uncorrected values are in fact 40 per cent too low, the total amount discharged by evapotranspiration would still be only about 2,000 cubic metres per hour.

103. Penman's formula for computing potential evapotranspiration is:

$$ETP = (\Delta/\gamma H + E_a) \;/\; (\Delta/\gamma + 1/SD)$$

Where:

γ = the constant of wet- and dry-bulb psychrometer (0.66 mb/°C).

Δ = the slope of the saturation vapour pressure curve at the mean temperature, T_a

H = net income radiation, in equivalent mm/day.

H = $R_c(1\text{-}r) - R_b$, where R_c is incoming radiation in equivalent mm, r is the albedo, and R_b is long wave re-radiation (in equivalent mm) calculated from the empirical formula: $R_b = \sigma T_a^4(0.56\text{-}0.09\sqrt{e_d})\,(1 - \mu m)$ where σ is Stefan's constant ($= 1.17 \times 10^{-7}$) cal. cm. ($^{-2}$ °K $^{-4}$day $^{-1}$), e_d is saturation vapour pressure at T_a, m is cloud cover in tenths, and μ is a variable depending upon cloud type. T_a is expressed in degrees Kelvin.

S = surface conductance factor

D = day length factor

E_a = the aerodynamic or advective term $= 0.26\,(0.5 + 6.21 \times 10^{-3}U_2)\,(e_a - e_d)$, where U_2 is wind speed at 2 metres in km/day, e_a is actual vapour pressure (mb), and e_d is saturation vapour pressure (mb).

104. This is a highly sophisticated formula that requires a considerable amount of data, not all of which were directly available for the project area. The method, however, provides a good approximation. Milthorpe concludes that: "The Penman relationship, as generally used, gives values which are likely to be as accurate as any obtained by most direct methods and does so much more conveniently".[14]

105. Some discussion of the individual terms of the formula, and of their derived or assumed values, is necessary for evaluation of the final result.

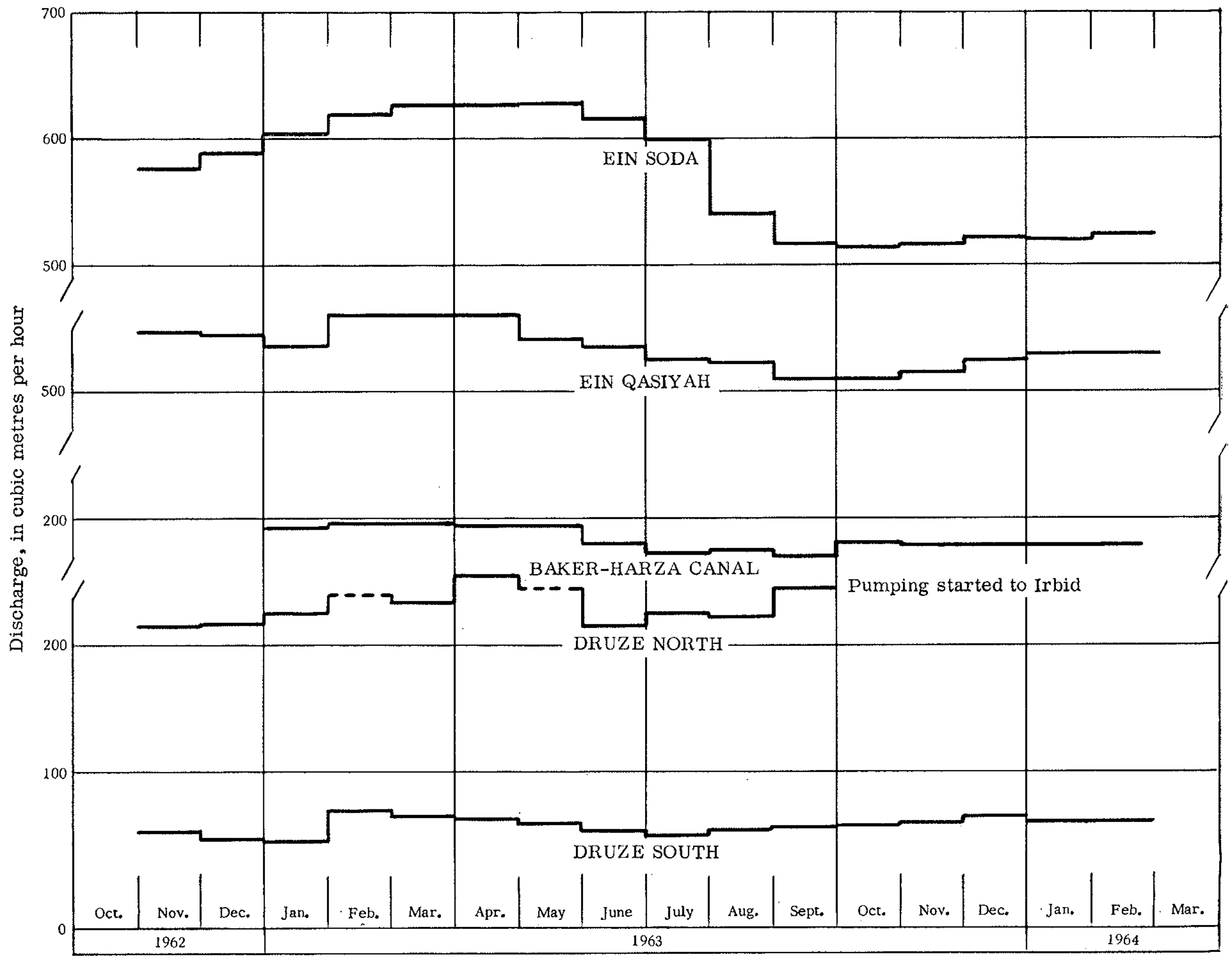
106. Δ at 21.6°C (the mean temperature for the last half of April) is 2.5.

107. R_c is taken as 560 cal/cm^2/day (April), based upon data for Irbid, as given by Wallen.

108. Two different values for albedo are used, one (r — 0.25) to compute losses from the standard green vegetative surface (which ideally would yield the same result as the Thornthwaite formula), and the second ($r = 0.05$) to compute open-water losses (which are

[14] F. L. Milthorpe, "The Income and Loss of Water in Arid and Semi-arid Zones", *Plant-Water Relationships in Arid and Semi-arid Conditions* (Paris, UNESCO, 1960).

Figure VI Hydrographs of spring discharges



used comparatively with pan data). The two results obtained are then pro-rated according to the estimated relative areas represented by each type of surface, to determine the evapotranspiration value to be applied to the planimetered areas. For April, this was taken as 35 per cent open water and 65 per cent vegetative surface.

109. According to Milthorpe, $^1/SD$ is 1.0 for open-water conditions and 1.3 for the standard green-vegetative surface.

110. Cloud cover in April was taken as 2 (in tenths), while μ is taken as 0.6, the value for medium-height clouds. Thus: $\mu m = 0.12$.

111. Average wet-bulb depression in April was 6°C, hence $e_a = 25\ mb$, and $e_d = 13\ mb$.

112. Using these data, the following values for evapotranspiration (in millimetres) were obtained:

(a) Open water 6.6;

(b) Standard green-vegetative surface, 4.8;

(c) Azraq swamps (average), 5.4.

113. The value obtained for open water is in fair agreement with Blaney's coefficient of 0.60 for evapotranspiration from Silver Lake in the Mojave Desert of California.[15] The value for the standard green-vegetative surface agrees well with the 30 per cent upward-adjusted Thornthwaite value of 4.6 millimetres and gives an annual evapotranspiration of about 1,750 millimetres. By applying the 5.4 millimetres figure to the planimetered swamp areas, the following discharges (in m^3/hr) were obtained:

Main Sheshan swamp	1,270
Baker-Harza swamp	400
Total Sheshan	1,670
Druze swamp	415
Total Azraq swamps	2,085

114. These values are consistent with observations in other, similar areas and indicate with a fair degree of accuracy the amount of water returned to the atmosphere from the Azraq swamps and springs. With the use of a formula of such complexity as Penman's, it would be possible to arrive at other values for evapotranspiration through the use of somewhat different assumptions. However, it is not possible to modify the

[15] H. F. Blaney, "Evaporation Study at Silver Lake in the Mojave Desert, California", Trans. American Geophysical Union, vol. 38 (1957) pp. 209 to 215.

data in any rational manner to arrive at a significantly larger figure. This would require unwarranted tampering with the values assigned to the individual parameters. Moreover, the results would be inconsistent with the findings of other investigators in this and similar areas.

115. The total estimated discharge of 2,085 m^3/hr exceeds by 390 m^3/hr the total discharge measured by weirs in April 1963. This ungauged discharge may be accounted for in several ways. Quality-of-water studies (chapter III) indicate that some of the shallow ground water moving into the Azraq depression from the south and south-east discharges into the swamp area and is ungauged, and that some of the ungauged discharge in the swamp area is contributed by ground-water underflow from the basalt area north of Azraq. Also, some of the ground water from the artesian aquifers in the Belqa Series probably rises through seeps in the bottom of the swamps and, thus, is not gauged by the weirs.

116. Data from evaporation pans or evaporimeters of any type should be used with caution in estimating evapotranspiration or actual evaporation from large bodies of water. Some investigators, for example Milthorpe, feel that this approach is risky. The general consensus, however, seems to be that so long as the limitations of such methods are recognized, they are useful for comparing data between stations in the same general area. For example, the only method for determining evapotranspiration that does not require elaborate instrumentation is Thornthwaite's, which gives results that are about 30 per cent too low for much of the Middle East. If perhaps four stations in Jordan were equipped to collect data for the application of Penman's formula, the evapotranspiration at intermediate points could be determined with a fair degree of accuracy on the basis of pan evaporation ratios. The recommended apparatus for this purpose is the United States Weather Bureau Class A evaporation pan. There are more data already available for this than for any other single type, and Mukammel concludes that the Class A pan is fundamentally superior to atmometers such as the Piche or Bellani.[16]

117. Figure VII shows average daily pan evaporation plotted against monthly mean temperature for both Azraq and Damascus, the latter data being taken from Wallen's report of 1962. Both stations show an odd hysterisis-like effect; for any given temperature, evaporation is distinctly less during the second half of the calendar year. Ward noted that this was owing to the fact that the temperature of the air lagged solar radiation, so that for a given temperature the amount of energy available for evaporation was greater in the spring than in the autumn.[17]

[16] E. I. Mukammel, "Evaporation Pans and Atometers", *Proceedings of Hydrology Symposium No. 2*. National Research Council of Canada (Toronto, 1961).

[17] R. C. Ward, "Observations of Potential Evapotranspiration" *Journal of Hydrology*, vol. 1, No. 3 (1963).

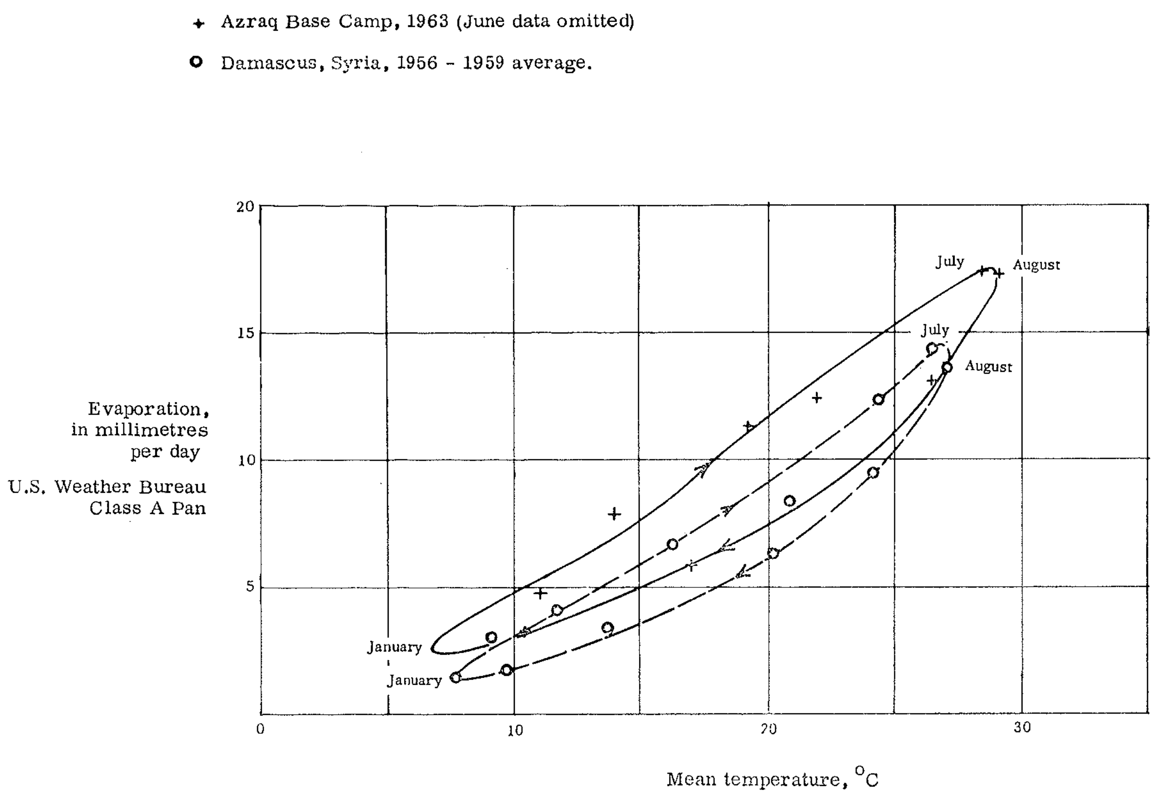
118. Qá Azraq is the low mud flat area that borders the spring-swamp areas on the south and east (map 3). The Qá plays a relatively small, but distinct, part in the hydrologic balance of the basin. Initially, it was believed that its only part in the balance was the disposal of sufficient water to maintain the level of the brine. However, when the ground-water contour map was prepared, it became evident that it must also be the area of disposal for ground water moving in from the south-east. No suitable method is available, either direct or indirect, for the determination of water-vapour loss from such an area. Unlike Chott Chergui, the surface of Qá Azraq is dry for much of the year and evapotranspiration formulae are inapplicable. Direct approaches, whether utilizing turbulent exchange or other methods, are not reliable, especially for such a relatively large area.

119. A description of the physical nature of the Qá is of interest, because of its somewhat unusual features, and as a guide to the general order of magnitude of water-vapour disposal that might be expected. Subsurface information was gathered from inspection of salt-works wells, and from three test pits. The surface of the Qá is covered with a saline crust which, when dry, expands and detaches itself from the deeper layers. The thickness of this crust ranges from 2 to 10 millimetres. In some places it is in direct contact with the underlying clays, but in other places is up-warped to a height of 60 millimetres above them, although the usual separation is only a few millimetres. It acts as a canopy that protects the clay surface from both wind and insolation. Below this crust there is generally a broken, stone-hard layer of clay, averaging 7 or 8 centimetres in thickness. Next is a red-brown, saline clay, which is moistened by capillary rise to a total depth of 1.3 to 1.5 metres, below which is a grey lacustrine marl. The brine occurs in this marl, which is of extremely low permeability. Note the slow recovery rate of the liquid in brine well OB-1 (figure IV). Prior to measurement, the well had been pumped for about 6 months at an average rate of not over 5 gallons per minute (gpm). The depth to the brine in the centre of the Azraq depression is about 1.75 metres; the depth increases gradually towards the periphery. The direct quantitative evaluation of water-vapour loss under the above conditions is not feasible. It has been established by previous studies that the losses decrease rapidly with increasing depth to the water-table. Todd states: ". . . and further that it decreases to an almost negligible rate for water tables three or more feet below ground surface".[18]

120. A factor which further reduces the effectiveness of Qá Azraq as a disposal medium for ground water is its periodic flooding. Because the Qá is the topographical low of the basin, it receives surface water from all directions and is covered with water from 2 to 4 months of each year. Therefore, there is

[18] D. K. Todd, *Ground Water Hydrology* (New York, John Wiley and Sons, 1959), p. 155.

Figure VII Temperature-evaporation relationships



no evaporation of brine during this period, which is followed by a further period of a few months, when the Qá is not flooded and soil moisture losses represent only disposal of the water that was infiltrated from the surface during the period of flooding. Thus, for roughly half of the year the Qá has no influence on the ground-water regimen.

121. The additional quantity of discharge from Qá Azraq, from wells and from small ungauged springs and seeps is estimated to be about 250 m³/hr from all sources. Thus, to the 2,085-m³/hr estimated discharge should be added 250 m³/hr as a separate value which does not too critically affect final estimates (see paras 124-126).

122. The other qás south of the basalt shield probably have a negligible effect on the ground-water regimen. There is little recharge to or disposal from them; their part in the hydrologic cycle is to provide evaporative areas for surface run-off. This is confirmed by wells which have been drilled in or immediately adjacent to qás. A test hole that was drilled in a small playa about 5 kilometres north-west of the Azraq police post was abandoned dry at a depth of 21 metres. The depth to the static water-level in well Hababiya No. 1, in the lower part of Qá Khanna, was 60 metres; and in Hammam No. 2, upper Qá Khanna, it was 72.2 metres. The static water-level in both wells was well below the bottom of the alluvial fill in the Qá.

3. *Wells*

123. Data on producing wells in the project area were provided by Mr. Kamel A. Kawar in a written communication in December 1964. Of the 25 wells listed, 16 are used for domestic supply and irrigation, 3 for domestic supply, 3 for domestic and live stock supply, 2 for irrigation, and 1 for domestic and industrial supply. Most of the wells are pumped for only a few hours a day during part of the year; 3 are pumped the year round. The estimated total discharge from all the wells was 524,500 cubic metres per year. The inventory includes wells Hammam No. 2, AZ-19, Tapline 6-A and Hababiya No. 3 around the periphery of the basin. The balance of the producing wells are grouped in and adjacent to Qá El-Azraq. The total discharge from wells is estimated to be only about 60 m³/hr.

E. Summary of hydrology

124. The estimates of evapotranspiration from the Azraq springs and swamps were made by two generally accepted methods. The value of 1,240 m³/hr obtained by the Thornthwaite method obviously is too low, and even the 30 per cent increase recommended by Wallen yields a value that still appears to be too low. The 2,085 m³/hr determined by Penman's formula is used in this report as the more nearly correct value.

125. The total estimated discharge of ground water from the aquifers at El-Azraq is 2,085 m^3/hr plus 250 m^3/hr. Of this amount, most of the 250-m^3/hr discharge from Qá Azraq and other sources is not practicably usable because of its generally poor quality and the low yields of wells in the central part of the Qá. Of the remaining 2,085 m^3/hr, 350 m^3/hr should be subtracted because this is the design capacity of the Azraq-Irbid water pipeline, which leaves a balance of 1,735 m^3/hr. However, the average annual discharge of the springs measured during the investigation (table 5) was about 100 m^3/hr less than the April discharge upon which the preceding calculations were based, so the quantity should be further reduced to 1,635 m^3/hr. Finally, not all natural ground-water discharge can be intercepted by wells even under ideal conditions, owing to limiting hydrologic factors. Therefore, a factor of 75 per cent was applied as the quantity practicably recoverable, which leaves roughly 1,200 m^3/hr as the net amount of water perennially available from the shallower aquifers in the project area.

126. Although the quantity of ground water perennially available for exploitation is limited, consideration must be given to the relatively large additional quantity of water that is in storage in the geologic formations. This quantity in storage was originally accumulated during the geologic past, when water gradually infiltrated and filled the more permeable subsurface rock units to a level where the surplus ground water was discharged at the land surface in the topographically low centre of the basin. Thus, the hydrologic regimen presently is in hydraulic balance and the water that is discharged at El-Azraq represents the annual surplus in excess of storage. Quantitative estimates of the volume of ground water in storage are beyond the scope of this study, but all indications point to a very large usable quantity in storage beneath the project area. If the Jordanian Government should decide to mine the stored water and export it to meet urgent municipal or industrial needs in other parts of Jordan, relatively large amounts probably could be pumped from storage for a long period of time. Should such a programme be decided upon, a more detailed investigation of the basin would be necessary to determine the long-term economic feasibility. Such an investigation would require the drilling and test pumping of many more wells at carefully selected sites in the basin.

III. CHEMISTRY OF THE WATER

A. Hydrochemistry

127. In an investigation such as this, quality-of-water studies serve a dual purpose; firstly, to provide information concerning the suitability of water for the use or uses intended; and secondly, to assist in the interpretation of the hydrology and geology of the area. Properly done, water analyses usually are among the best quantitative data available.

128. The analyses listed in table 6 were made in the Azraq-project laboratory. Sodium was determined by difference and total dissolved solids by summation of the individual components, rounded off to the next higher 5 or 10 parts per million (ppm). Hem states that "As a general rule of thumb, the computed dissolved solids are most reliable than the determined residue on evaporation for concentrations above 1,000 ppm".[1] Standard methods were used throughout except for sulfate, which was determined by photoelectric turbidimetry. Boron was not determined; however, an analysis of the Sheshan Springs water, believed to be from Ein Qasiyah, made by the Salinity Laboratory of the United States Department of Agriculture in 1962, showed only 0.4 ppm boron, so probably this element does not exist in harmful quantity in any of the waters that might otherwise be considered for irrigation use.

[1] J. D. Hem, *Study and Interpretation of the Chemical Characteristics of Natural Water*, United States Geological Survey Water-Supply Paper 1473 (Washington, D.C., 1959).

B. Quality-utilization considerations

129. The composition and concentration of salts in the natural waters of the basin vary widely. Total dissolved solids range from 200 ppm in Hababiya No. 3 well to 245,000 milligrammes per litre (mg/litre) in well OB-1 in the brine field in Qá Azraq. The composition of much of the water is notable for high percentages of sodium and chloride, and, in some cases, of sulfate also. The general picture is that of typical limestone-dolomite waters that have had more or less extensive contact with evaporites and have been subject to cation exchange in some cases. The range of relative compositions is shown in figure VIII. Minor constituents are unremarkable and none were found that were of any interpretative value. Hydrogen sulfide, in quantities up to 3 ppm, is a frequent component in waters from the B 2 and B 3 aquifers, but this is characteristic of waters from bituminous rocks.

130. The Druze springs receive their water from the basalt shield area, but the composition is not typical of basaltic waters, which are usually lower in sulfate and choloride and somewhat higher in silica. This indicates that the basalt is not the aquifer, at least not over the entire area, but rather a recharge formation through which water percolates downward into the underlying flint-chalk-limestone aquifers of the Belqa Series. These waters, in particular, exhibit evidence of cation exchange, with a ratio of calcium plus magnesium to bicarbonate of less than unity. Such exchange

Table 6

CHEMICAL ANALYSES OF WATER IN THE AZRAQ BASIN, 1962-1964
(RESULTS IN EQUIVALENTS PER MILLION EXCEPT AS INDICATED)

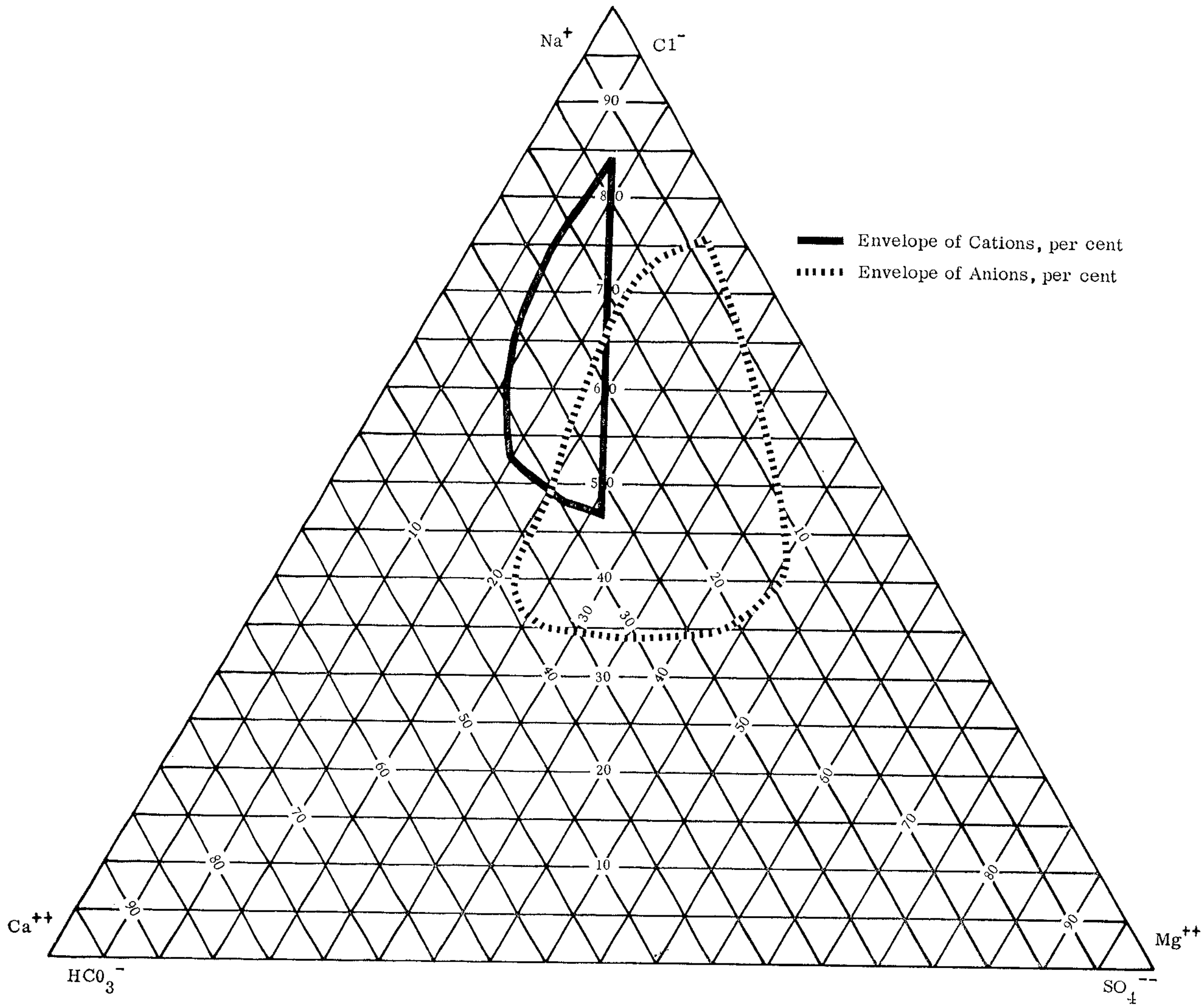
Well or spring	*Calcium (Ca)*	*Magnesium (Mg)*	*Sodium (Na)*	*Bicarbonate (HCO3)*	*Sulfate (SO4)*	*Chloride (Cl)*	*Total dissolved solids (ppm)*	*pH*	*Specific conductance (micromhos at 25° C)*	*Irrigation class*	*Other properties (ppm)*	*Sodium adsorption ratio (SAR)*
						Well water						
AZ-1, B4 aquifer	1.00	0.82	5.02	2.40	1.35	3.05	395	8.2	620	C2-S1	NO_3=2.5, PO_4=0.1	5.3
AZ-1, B3 aquifer[a]	115	69	689	78[b]	90	695	50,000	8.4	—	—	H_2S=3, PO_4=0.28	—
AZ-1, B2 aquifer[a]	4.70	2.79	12.41	4.40	7.00	8.50	1,180	7.4	1,550	C3-S2	SiO_2=20 H_2S=2, Fe=0.65	6.4
AZ-1, Kurnub aquifer[a]	7.60	2.96	11.60	3.19	8.20	10.77	1,350	7.8	2,000	C3-S2	SiO_2=19	5.1
AZ-3	9.00	9.02	15.97	7.84	7.53	18.62	1,920	7.1	2,600	C4-S2	H_2S=2	5.3
AZ-4	9.00	6.60	18.25	5.60	8.15	20.10	1,960	7.7	3,050	C4-S2		6.5
AZ-5	7.10	6.31	19.44	3.10	8.55	21.20	1,930	8.2	2,900	C4-S2	Fe=0.50	7.5
AZ-8[a]	1.00	0.66	4.71	2.10	1.39	2.88	380	8.3	640	C2-S1		5.2
AZ-10	5.40	4.03	7.99	3.00	4.52	9.90	1,010	—	1,650	C3-S1		3.7
AZ-12	0.70	0.58	3.72	2.00	1.25	1.75	310	8.0	490	C2-S1		4.7
AZ-13[a]	3.70	4.27	59.56	2.60	8.25	56.58	4,000	7.9	6,900	—		30
AZ-14	61	69	589	0.4	64	654	42,000	—	—	—	Sp. Gr.= 1.031	
AZ-15	9.60	5.72	25.68	3.95	14.35	22.70	2,500	7.2	3,600	C4-S3		9.3
AZ-19	7.00	6.99	12.34	5.81	7.40	13.12	1,510	—	2,150-2,380[d]	C4-S2 -C4-S2		4.7 —
AZ-21	3.80	2.95	23.32	7.10	6.47	16.50	1.760	7.8	2,800	C4-S3		13
AZ-22	7.00	3.53	13.87	4.20	9.15	11.05	1,500	8.0	2,100	C3-S2	SiO_2=40	6.0
AZ-23	4.10	0.82	5.50	5.11	2.71	2.60	600	7.8	880	C3-S1		3.5
PA-3	1.90	1.24	4.46	2.80	1.74	3.06	440	7.8	660	C2-S1		3.6
PA-4[a]	3.60	2.30	10.40	4.33	6.43	5.54	980	8.2	1,120	C3-S2		6.0
PA-6	1.50	0.66	5.25	2.45	1.58	3.38	435	8.0	670	C2-S1		5.0
Shomari No.	8.40	4.76	10.24	4.01	8.94	10.45	1,510 1,630[d]	7.4	2,250	C3-S2		4.0
Hammam No. 2	0.80	0.59	2.45	1.91	0.67	1.24	215	8.2	360	C2-S1	Fe=0.06	2.9
Tapline Well	1.70	1.03	5.72	1.00	3.02	4.43	525	8.2	880	C3-S2	SiO_2=14	4.9
Hababiya No. 3	0.55	0.66	2.07	1.67	0.48	1.13	200	8.1	345	C2-S1		2.7
OB-1 Brine Well	92	121	3,914	66[b]	418	3,660	245,000[c]	8.4	—	—	Sp. Gr.= 1.155, SiO_2=110 PO_4=0.45	—
Ein Soda	1.85	1.66	18.29	2.90	3.24	15.66	1,270	8.3	2,000	C3-S3	SiO_2=18	14
Ein Qasiyah	1.70	0.92	10.70	1.91	2.13	9.28	780	8.1	1,290	C3-S2	F=0.40	9.4
Druze North	0.65	0.58	3.89	2.00	1.36	1.76	330	8.2	475	C2-S1	F=0.10 SiO_2=27	6.4
Druze South[a]	0.70	0.58	4.55	2.41	1.36	2.06	340	8.3	510	C2-S1		5.7
Ein Unquiyah	1.00	0.49	5.10	2.60	1.59	2.40	385	7.8	595	C2-S1	SiO_2=19	5.9
Baker-Harza Canal[a]	2.40	1.79	8.61	3.84	2.50	6.46	740	8.0	1,190	C3-S2		5.9

[a] Data not shown on chemical-type-of-water map.
[b] Includes normal carbonate.
[c] Milligrammes per litre.
[d] Later sample.

may be ascribed to contact of the water with montmorillonite or similar minerals with a high exchange capacity, which have been formed by the devitrification of glasses in the basalt.

131. Generally, water for irrigation should be of such quality that it will not adversely affect the productivity of the land to which it is applied. Certain properties of the water are of major importance in determining the effect that the water will have on soil productivity. These properties are the mineralization, or total concentration of the dissolved salts, the relative proportion of sodium to calcium and magnesium, the concentration of boron or other elements that might be toxic to plants and, for some water, the concentration of bicarbonate in excess of the concentrations of calcium and magnesium.

Figure VIII Range of chemical composition of Azraq Basin water



132. High total concentrations of dissolved salts in irrigation water tend to cause an increase of salts in the soil solution and may cause the soil to become saline. Because all plants take in water by osmosis, a favourable balance must be maintained between salts within a plant and salts in the soil solution. When the total concentration of salts in the soil solution becomes too high for plants to get an adequate amount of water, or when the concentration of certain salts in the soil solution becomes so high as to be toxic, the growth of the plants is adversely affected. The tendency of irrigation water to cause an accumulation of salts in the soil is called the salinity hazard of the water. The specific conductance of the water is used as an index of the salinity hazard.

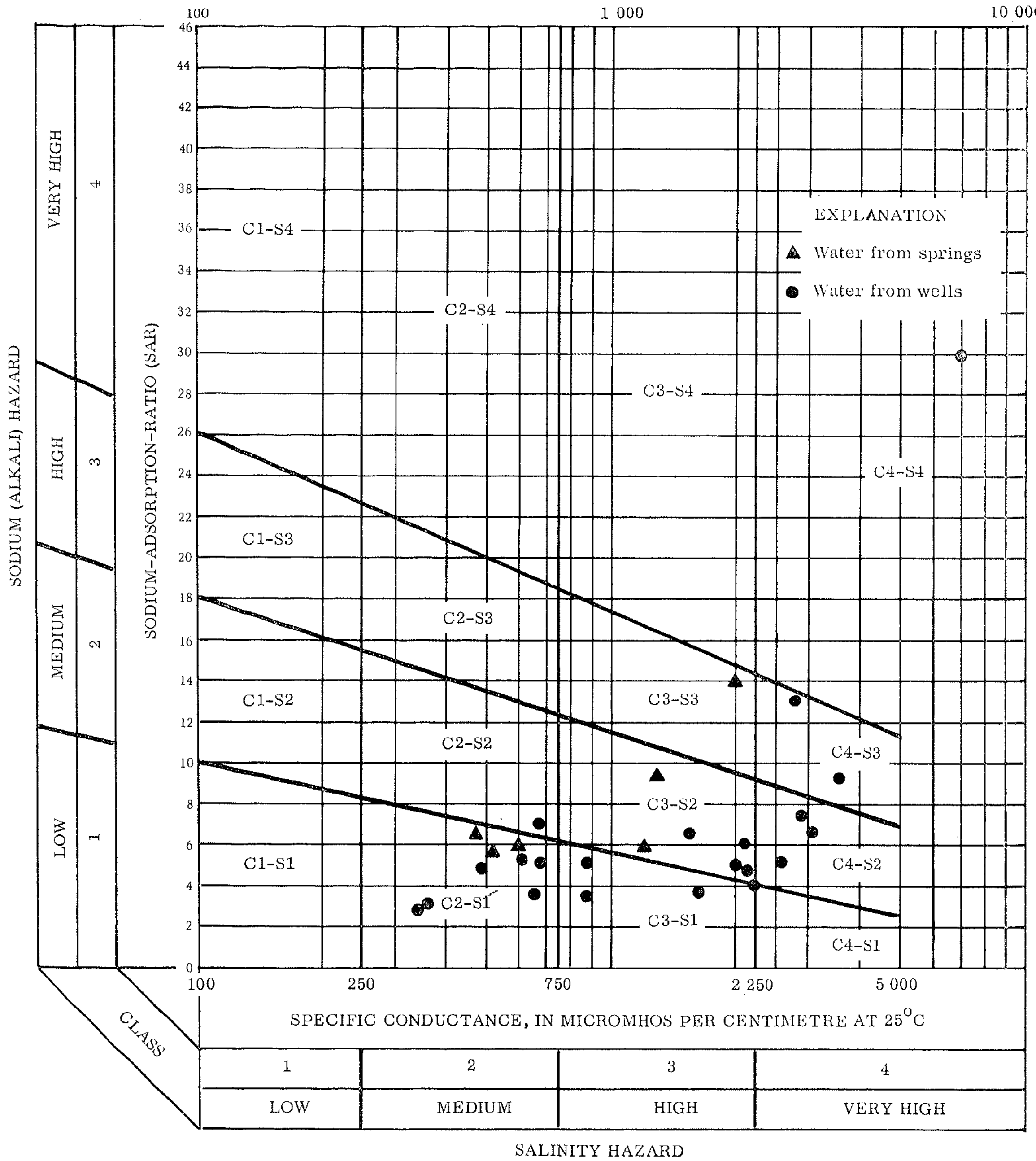
133. High concentrations of sodium relative to the concentration of calcium and magnesium in irrigation water can adversely affect soil structure. Cations in the soil solution become fixed on the surface of fine soil particles; calcium and magnesium tend to flocculate the particles, but sodium tends to deflocculate them. Flocculation gives the soil looseness, provides good penetration by water and air, and generally gives the soil good tillage properties. Deflocculation promotes packing and prevents free movement of air and water. The adverse effect on soil structure caused by high concentrations of sodium in the irrigation water is called the sodium hazard of water. An index used for predicting the sodium hazard of a water is the sodium-adsorption ratio (SAR), which is defined by the equation:

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{+2} + Mg^{+2}}{2}}}$$

where Na^{+}, Ca^{+2}, and Mg^{+2}, are in equivalents per million.[2]

[2] United States Department of Agriculture, Salinity Laboratory Staff, *Diagnosis and Improvement of Saline and Alkali Soils*, Agriculture Handbook 60 (Washington, D.C., 1954), p. 72.

Figure IX Classification of the water for irrigation
(Diagram after U.S. Salinity Lab. Staff, 1954)



134. Most of the mineral constituents of water are essential plant nutrients. However, some of these same constituents may, if present in sufficiently high concentrations, interfere with normal plant nutrition and growth. High concentrations in soil solutions of such constituents as sodium, calcium, magnesium, chloride, sulfate, and bicarbonate have been reported to be associated with toxic reactions in some plants.[3] Boron is essential to the normal growth of all plants, but the concentrations needed are small; when these concentrations are exceeded, injury to the plants may result. Boron contents as low as 1.0 ppm are toxic to boron-sensitive plants; if the boron content is too low—less than 0.3 ppm—the water may leach boron from the soil and reduce its productivity.[4]

135. High concentrations of bicarbonate in irrigation water may cause calcium and magnesium carbonates to precipitate in the soil as the water is concentrated by evapotranspiration. Precipitation of calcium

[3] Ibid., pp. 61 to 63.

[4] F. M. Eaton, "Deficiency, Toxicity, and Accumulation of Boron in Plants", *Journal of Agricultural Research,* vol. 69 (1944).

and magnesium results in an increase in the proportionate amount of sodium in the water; the effect on the soil is the same as if the sodium hazard of the irrigation water had been high.

136. The salinity hazard and sodium hazard of the water are determined from a diagram (figure IX) in which the SAR values given in table 6 are plotted. Interpretation of the diagram by the United States Salinity Laboratory Staff is as follows:[5]

(a) Low-salinity water (C 1) can be used for irrigation with most crops on most soils with little likelihood that soil salinity will develop. Some leaching is required, but this occurs under normal irrigation practices except in soils of extremely low permeability;

(b) Medium-salinity water (C 2) can be used if a moderate amount of leaching occurs. Plants with moderate salt tolerance can be grown in most cases without special practices for salinity control;

(c) High-salinity water (C 3) cannot be used on soils with restricted drainage. Even with adequate drainage, special management for salinity control may be required and plants with good salt tolerance should be selected;

(d) Very high salinity water (C 4) is not suitable for irrigation under ordinary conditions, but may be used occasionally under very special circumstances. The soils must be permeable, drainage must be adequate, irrigation water must be applied in excess to provide considerable leaching and crops with an extremely high salt tolerance should be selected.

137. The classification of irrigation waters with respect to SAR is based primarily on the effect of exchangeable sodium on the physical conditions of the soil. Sodium-sensitive plants may, however, suffer injury as a result of sodium accumulation in plant tissues when exchangeable sodium values are lower than those effective in causing deterioration of the physical condition of the soil, as noted below:

(a) Low-sodium water (S 1) can be used for irrigation on almost all soils with little danger of the development of harmful levels of exchangeable sodium. However, sodium-sensitive crops, such as stone-fruit trees and avocados, may accumulate injurious concentrations of sodium;

(b) Medium-sodium water (S 2) will present an appreciable sodium hazard in fine-textured soils having a high cation-exchange capacity, especially under low-leaching conditions, unless gypsum is present in the soil. This water may be used on coarse-textured or organic soils with good permeability;

(c) High-sodium water (S 3) may produce harmful levels of exchangeable sodium in most soils and will require special soil management—good drainage, high leaching and organic matter additions. Gypsiferous soils may not develop harmful levels of exchangeable sodium from such waters. Chemical amendments may be required for replacement of exchangeable sodium, except that amendments may not be feasible with waters of very high salinity;

(d) Very high sodium water (S 4) is generally unsatisfactory for irrigation purposes except at low and perhaps medium salinity, where the solution of calcium from the soil or use of gypsum or other amendments may make the use of these waters feasible.

138. Each class in the diagram includes a wide range in salinity. For a particular water, the relative position of the points within the class should be considered and not the class alone. Water having a specific conductance of 760 micromhos per centimetre is certainly much better than water having a specific conductance of 2,240 micromhos per centimetre; nevertheless, both are classed as C 3.

139. The designers of the diagram point out that:

> "In the classification of irrigation waters, it is assumed that the water will be used under average conditions with respect to soil texture, infiltration rate, drainage, quantity of water used, climate, and salt tolerances of crop. Large deviations from the average for one or more of these variables may make it unsafe to use what, under average conditions, would be a good water; or may make it safe to use what, under average conditions, would be a water of doubtful quality."[6]

140. The chemical type of water in the Azraq area and the areas in which water of a given chemical type predominates are shown on map 5. The lines that divide the salinity classes should not be considered as absolutely precise, since data for some areas are sparse. Generally speaking, however, they are correct and permit several basic conclusions to be drawn. The C 2 area lying generally in the north-west quadrant is the only source of water of really satisfactory quality. Water from wells in the Shomari drainage basin is of marginal quality and yields generally would be too low for irrigation use except in a limited area along the axis of drainage. Additional C 3 water might be available in some quantity from wells located north-east of the Druze Springs, but the cultivable land available is severely limited. The C 4 areas should be excluded from further consideration, because the ground water is of very poor quality and the yield from the individual wells is small.

141. Routine checks of the electrical conductivity of water from selected sources (table 7) showed no significant variations during the period of study, except for the Shomari No. 1 irrigation well at Shomari Farm. Water from this well shows distinct evidence of quality deterioration, probably owing to irrigation return water, and illustrates the need for caution in the methods of application of irrigation water in the area.

[5] United States Salinity Laboratory Staff, op. cit., p. 80.

[6] Ibid.

Table 7

WATER-QUALITY CHECKS
(ALL VALUES ARE ELECTRICAL CONDUCTIVITY IN MICROMHOS PER CENTIMETRE AT 25°C)

1963

Hammam No. 2 Well		*Baker-Harza Canal*		*Ein Soda Springs*		*Ein Qasiyah Springs*		*Druze North Spring*		*Shomari No. 1 Well*	
Date	*Spec. cond.*	*Date*	*Spec. cond.*	*Date*	*Spec. cond.*	*Date*	*Spec. cond.*	*Date*	*Spec. cond.*	*Date*	*Spec. cond.*
15 Feb.	390	27 Mar.	1190	8 Jan.	2000	8 Jan.	1290	8 Jan.	460	21 Jan.	2150
3 Mar.	360	29 Apr.	1200	13 Feb.	2060	13 Feb.	1370	5 Mar.	480	2 Mar.	2200
30 Mar.	395	1 June	1150	28 Mar.	2150	28 Mar.	1330	27 Mar.	475	31 Mar.	2300
6 June	405	2 July	1140	29 Apr.	2080	29 Apr.	1380	29 Apr.	515	1 May	2250
3 July	405	31 July	1130	1 June	2100	1 June	1490	1 June	500	6 June	2100
31 Aug.	385	31 Aug.	1080	2 July	2030	2 July	1300	2 July	490	1 July	2190
30 Sept.	400	30 Sept.	1090	31 July	2030	31 July	1230	31 July	490	31 July	2100
		28 Oct.	1130	31 Aug.	2050	31 Aug.	1260	31 Aug.	480	29 Aug.	2150
		30 Nov.	1130	30 Sept.	2030	30 Sept.	1400	29 Sept.	520	28 Sept.	2420
		30 Dec.	1180	28 Oct.	2050	28 Oct.	1390	28 Oct.	490	31 Oct.	2180
				30 Nov.	2050	30 Nov.	1340	30 Nov.	495	29 Nov.	2640
				30 Dec.	2150	30 Dec.	1260	29 Dec.	490		
1964											
								8 Jan.	500	17 Jan.	3000

142. From the standpoint of municipal supply, the ground water derived from the basalt-shield area is of satisfactory quality and is the only water that can be recovered in quantities large enough to justify exportation from the basin. The quality of water from 4 wells that produced from the sedimentary formations, AZ-1 (except for the B 3 aquifer), AZ-8, AZ-11 and AZ-12, and from the Druze pools, insofar as the analyses were carried, meets the United States Public Health Service standards for drinking water, shown in table 8.[7] Analyses for trace constituents were not made on all of these samples because initial testing showed them to be well below the limits of tolerance. Facilities were not available for the determination of other trace constituents such as cyanide and phenols, but these are normally associated with industrial wastes, which are non-existent over the catchment area. Hardness is generally below 100 ppm (as $CaCO_3$). Pollution over the catchment area is negligible, but standard bacteriological controls and checks of the water should be maintained in the future.

[7] American Water Works Association, *Journal of American Water Works Association*, vol. 53, No. 8 (1961), pp. 941 to 943.

C. Determination of the principal recharge area

143. The chemical characteristics of the various types of water (table 6) were used to determine the

Table 8

DRINKING-WATER STANDARDS, CHEMICAL CHARACTERISTICS
(MILLIGRAMMES PER LITRE)

These substances should not be present in excess of the listed concentrations if a better supply is available.

Alkyl benzene sulfonate (ABS)	0.5
Arsenic (As)	0.01
Chloride (Cl)	250.0
Copper (Cu)	1.0
Carbon chloroform extract (CCE)	0.2
Cyanide (CN)	0.01
Fluoride (F)	a
Iron (Fe)	0.3
Manganese (Mn)	0.05
Nitrate (NO_3)	45.0
Phenols	0.001
Sulfate (SO_4)	250.0
Zinc (Zn)	5.0
Total dissolved solids	500.0

The presence of any of these substances in excess of the concentration listed shall constitute grounds for the rejection of the supply.

Arsenic (As)	0.05
Barium (Ba)	1.0
Cadmium (Cd)	0.01
Chromium (Cr^{6+})	0.05
Cyanide (CN)	0.2
Fluoride (F)	a
Lead (Pb)	0.05
Selenium (Se)	0.01
Silver (Ag)	0.05

Source: United States of America, Public Health Service, 1961.

Maximum permissible fluoride depends upon annual average of maximum daily air temperature and ranges from 0.8 to 1.7 mg/litre.

principal recharge area and to calculate the percentage of the total water that is derived from that area. Map 5 (in pocket) shows that the waters sampled in the C 2-quality area, which is a rough quadrant comprised of the basalt shield and Wadi er-Ratam, are relatively low in dissolved-solids content and are also quite similar in over-all chemical composition. The water of Druze Springs belongs to this family.

144. Burdon and other previous investigators recognized an indirect familial relationship between the waters of the Sheshan Springs and that of Druze Springs. However, the analyses show that the water from Ein Qasiyah and Ein Soda Springs has a higher percentage of sodium than any other water examined, except for water from the brine field. More significantly, the ratio of chlorides to sulfates is more than 4 to 1 for the Sheshan water; but for most of the other waters, except for water from the brine field, the ratio is less than 3 to 1. This leads to the conclusion that the water from Sheshan Springs is contaminated with a very small amount of brine; no other blend would be likely to produce the distinctive composition of the water from these springs. The chemical composition of the composite water from Sheshan Springs, weighted for proportion of discharge from the two springs, is:

Ca	Mg	Na	HCO_3	SO_4	Cl	TDS
(All ions expressed in epm)						
1.78	1.31	14.75	2.43	2.71	12.68	1,040 ppm

145. The percentage of sodium is 82.5; the chloride to sulfate ratio is 4.7 to 1. From this point on, the reasoning is best set forth in steps, as given below:

(a) The total dissolved-solids content of water from Sheshan Springs is lower than that of most of the water analysed from the C 3-C 4 area. Therefore, some must come from the C 2 area;

(b) The quality of water from Shomari No. 1 well is taken as being representative of contributions from the C 3-C 4 area. This is conservative, because the average total dissolved-solids content of water from C 3-C 4 area would be less than the 1,630 ppm total dissolved-solids content (later sample, table 6) of Shomari No. 1 well water;

(c) It was established experimentally that the amount of brine of OB-1-well quality required to establish a blend of the quality shown on the previous page lies between two and three-tenths of 1 per cent, which is negligible from a volumetric standpoint;

(d) However, 0.2 per cent of brine will contribute 490 ppm total dissolved-solids to the C 2 water, making a minimum of 790 ppm (300 ppm from Druze Springs water); and the maximum amount of water from Shomari No. 1 well that can be blended to produce a total dissolved-solids content of 1,040 ppm is 19 per cent;

(e) The blend described in (d) does not conform to the characteristic composition of Sheshan springs water. The chloride to sulfate ratio is too low, indicating too high a percentage of Shomari No. 1-well water, which has a ratio less than unity. Also, the quality of Druze Springs water is not exactly representative of the average quality of water from the C 2 area, which is of somewhat poorer quality. The quality of water from well PA-3 (440 ppm total dissolved-solids) was taken as being more nearly representative of the C 2 area, especially for ground water entering from the Wadi er-Ratam area;

(f) By taking the facts given above into account, a blend corresponding very closely to the composite Sheshan Springs water was derived. The required composition is 70 per cent Druze Springs water, 20 per cent PA-3 well water, 10 per cent Shomari No. 1 well water and 0.25 per cent brine, which gives the following composition:

Ca	Mg	Na	HCO_3	SO_4	Cl	TDS
(all ions expressed in epm)						
1.90	1.43	14.43	2.48	3.25	12.03	1,060 ppm

The percentage of sodium is 81.3; the chloride to sulfate ratio is 3.7 to one. These values could be adjusted still further to give an even closer correspondence, but this would imply a degree of accuracy that does not exist. It may be further demonstrated that nearly all of the C 3-C 4 water discharges through Ein Soda Springs;

(g) On the basis of the above computations, the distribution of flow into the main Sheshan springs is believed to be as follows: (a) 1,065 m^3/hr from the C 2 area; and (b) 120 m^3/hr from the C 3-C 4 area. The discharge data used in this development were contemporaneous with the quality determinations;

(h) Similar computations also show that water in the Baker-Harza Canal can be duplicated in quality by blending 85 per cent of C 2-area water, 15 per cent of Shomari No. 1 well water and slightly less than one-tenth of 1 per cent of brine. Then, the distribution of flow from the C 2 area is 165 m^3/hr and from the C 3-C 4 area, 30 m^3/hr.

(i) The flow from the Druze springs is of C 2 quality. Hence, the total distribution (in m^3/hr) of surface discharge is:

	C 2 area	*C 3-C 4 area*
Sheshan Springs	1,065	120
Baker-Harza Canal	165	30
Druze Springs	315	—
	1,545 (91 per cent)	150 (9 per cent)

146. It was estimated that the total flow to the springs and swamps at El-Azraq is about 2,085 m^3/hr, of which about 390 m^3/hr is not gauged. Of this un-

Table 9

CHEMICAL ANALYSIS OF BRINE FROM SALT-PRODUCTION WELL, ALI HURAISHEL

	ppm	epm
Silica (SiO_2)	3.8	
Iron (Fe)	.00[a]	
Aluminum (Al)	1.8[a]	
Manganese (Mn)	.00[a]	
Copper (Cu)	.00[a]	
Zinc (Zn)	1.0[a]	
Calcium (Ca)	460	22.95
Magnesium (Mg)	656	53.97
Sodium (Na)	70,500	3,066.75
Potassium (K)	2,080	53.19=3,196.86
Bicarbonate (HCO_3)	76	1.25
Carbonate (CO_3)	0	.00
Sulfate (SO_4)	18,500	385.17
Chloride (Cl)	99,800	2,815.36
Fluoride (F)	1.7	.09
Nitrate (NO_3)	7.6	.12=3,201.99
Phosphorus (as PO_4)	.00	
Dissolved solids		
Calculated	192,000	
Residue on evaporation at 180°C	194,000	
Hardness as $CaCO_3$	3,850	
Noncarbonate hardness as $CaCO_3$	3,790	
Alkalinity as $CaCO_3$	62	
Free Carbon Dioxide (CO_2) (Calc.)	9.6	
Specific conductance		
(micromhos at 25°C)	117,000	
pH	7.1	
Color	5	
Boron (B)	.16	
Temperature (°C)	23	
Density g/ml	1.152	

[a] In solution at time of analysis.

gauged water, 150 m^3/hr comes from the C 4 area. Assume that, of the remainder, 140 m^3/hr comes from the C 3-C 4 area and 100 m^3/hr from the C 2 area. The C 2-area discharge is then 1,645 m^3/hr, or 79 per cent of the total, and C 3-C 4 contributions are 440 m^3/hr, or 21 per cent of the total.

147. Comparison of the small yields of most of the wells drilled in the C 3-C 4 areas with the much larger yields of wells AZ-1, AZ-8 and AZ-12 indicates that these results are reasonable. Although no fine degree of accuracy is claimed for this method, it is felt that no gross error is involved; and it is concluded that somewhat less than 25 per cent of the potential recharge area provides about 80 per cent of the water that is discharged at El-Azraq.

D. The brine reservoir

148. In a preliminary memorandum submitted to the Central Water Authority on 27 January 1963, attention was drawn to the possibility of salt-water intrusion from the brine field underlying Qá Azraq between Sheshan and Druze Springs. A sample of water from dug well OB-1, which is used for salt production from the brine field, contained about 245,000 mg/litre of dissolved solids composed primarily of sodium chloride. The density was determined by hydrometer to be 1.155. Application of this value in the Ghyben-Hertzberg formula indicates a depth of 8.6 feet of fresh water below base level for every foot of fresh water above base level.[8] The salt water-fresh water interface thus determined is theoretical; under natural conditions a zone of mixing extends both above and below the theoretical interface. Such a zone of mixing reduces the margin of safety available for lowering the level of the fresh ground water.

149. The extent of brine intrusion that can be caused by a small displacement of the existing equilibrium is illustrated by conditions at well AZ-9, near the edge of the brine field. Upon completion of this well, a 2-hour bailing test was made at an average rate of 85 gpm. Water quality at the beginning and at the end of this short test was:

	Start	*Finish*
Conductivity, (micromhos/cm)	2,900	3,950
Chlorides, (ppm)	770	1,150

[8] A. Hertzberg, "Die Wasserversorgung Einiger Norseebaden" (The Water Supply for Several North Sea Resorts), *Jour. Gashelenchtung u. Wasserversorgung*, Jahrb. 44 (Munich, 1901), pp. 815 to 819 and 842 to 944.

150. This emphasizes that the brine is so highly concentrated that only a very small amount of mixing will contaminate the good water. Although it seems probable that the design rate of pumping from the Druze north pool will not have serious effects, no plans should be made for additional pumping from any of the pools, or from wells near by. Withdrawal of water from aquifers in the Belqa Series should be only from wells drilled in the area recommended on map 4.

151. Field data are inadequate to predict under what circumstances or where salt-water intrusion could occur. However, the brine does exist in close proximity to the springs and the admixture of only 1 per cent of brine with fresh water would render the latter virtually unusable for either irrigation or domestic purposes. When the memorandum of 27 January 1963 was prepared, it was believed that the Sheshan group of springs might be protected from brine encroachment by a fault barrier. Subsequent water-quality studies indicate that this is not the case and that both the Ein Qasiyah and the Ein Soda springs show a very small degree of mixing with brine. This was discussed in paras. 144-148 of this chapter. At the completion of the Special Fund study, there was no evidence of brine intrusion with the Druze North pool, which is used as the principal source of supply for the Azraq-Irbid water pipeline. Weekly checks on water samples taken from the pool showed no indication of deterioration in quality. It should be noted, however, that pumpage into the pipeline amounted to an average of 208 m^3/hr in December 1963, 129 m^3/hr in January 1964 and only 93 m^3/hr in February 1964. Periodic checks, preferably daily, of the electrical conductivity should be continued in the future for pumping rates more nearly approaching the design rate of 350 m^3/hr, in order to detect impending deterioration in the quality of the water.

152. A sample of brine was collected on 26 July 1964 from the Ali Huraishel salt-production well, which is 4 kilometres south-east of brine well OB-1, and was analysed by the Water Resources Division of the United States Geological Survey at Washington, D.C. The results of the analysis are in table 9.

IV. GROUND WATER IN THE STRATIGRAPHIC UNITS

A. Aquifer-testing procedures

153. Pre-existing and project wells were tested for yield and drawdown by several methods. Some of the wells were bailer tested upon completion; that is, the well was bailed rapidly for a period ranging from 1/3 to 2 hours, the drawdown measured at the end of the bailing and the discharge from the bailer averaged. Bailing tests have limited usefulness; the data usually indicate only whether or not the well has a sufficient yield and small enough drawdown to warrant further testing by other methods.

154. Slug-injection tests were made on some of the wells in order to estimate the coefficient of transmissibility (T) of the aquifer. Ferris and Knowles described the procedure for and the limitations of the method.[1] To make the test, a known volume, or "slug", of water is instantaneously injected into the well and water-level measurements of the declining head are made in rapid succession after the injection. For artesian aquifers, the coefficient of transmissibility can be solved graphically from a straight-line plot of the measured data. The equation is written:

$$T = \frac{114.6q\ (1/tm)}{s}$$

where

T = gallons per day per foot (gpd/ft),
s = the residual head after the injection of a slug of water,
q = the volume of the slug and
$1/tm$ = the reciprocal of time in minutes since injection of the slug.

155. According to Ferris and Knowles, "Use of the slug-injection test should be limited to fully developed wells that are open to the full thickness of an artesian aquifer of small or moderate transmissibility—less than 50,000 gpd per ft. The test probably cannot be used to determine the transmissibility of most water-table aquifers. Because the coefficient of transmissibility determined from this test generally applies only to the material close to the well, indiscriminate use of the results can lead to erroneous conclusions."[1] They also state that, "If the observed data from a slug-injection test do not plot on a straight line, the well may be in need of additional development."[1] Most of the wells tested did not meet the basic requirements given above, and slug-injection test data for most wells tested diverged widely from a straight line, indicating lack of development. Thus, most of the data from the slug-injection tests were unreliable.

156. Pumping tests were made on selected wells in the area adjacent to El-Azraq and on a well on the western edge of the project area. The objective was to obtain useful information on the specific capacity and coefficient of transmissibility of potential aquifers. However, results of most of the tests were not satisfactory owing to poor test-pump performance, widely fluctuating discharge rates and pump-engine stoppage. Most of the pumping tests provided only data on specific capacity and maximum drawdown during a 24-hour period of pumping; data sufficiently reliable to determine the coefficient of transmissibility were obtained for only 2 wells.

[1] J. G. Ferris, and D. B. Knowles, *The Slug-Injection Test for Estimating the Coefficient of Transmissibility of an Aquifer*, United States Geological Survey Water-Supply Paper 1536-I (Washington, D.C., 1963), pp. 299 to 304.

157. Methods of determining the coefficient of transmissibility of a water-bearing material involve an analysis of the rate of decline in the water-level of an aquifer as water is removed by pumping or of the rate of rise in the water-level after pumping has stopped. During a pumping test, the water-level is measured in the pumped well before pumping begins and at periodic intervals during the test; for a recovery test, the water-level is also measured periodically after the pumping stops until the rate of recovery becomes very slow. The equipment used to make the tests included a deep-well turbine pump with driving engine, an electric-contact tape for measuring depth to water, a stopwatch for timing the measurements and a Sparling current meter for measuring pump discharge. In some cases, the discharge was estimated by using the method and tables listed by Anderson.[2]

158. Non-equilibrium formulae for determining the coefficient of transmissibility by discharging-well methods assume that the aquifer test is made under the following conditions: "The aquifer is homogenous and isotropic and is of infinite areal extent; the well penetrates the entire aquifer; the well diameter is infinitesimal; and the water removed from storage is discharged instantaneously with decline of head."[3] Although it is recognized that an infinite aquifer is not found in nature, the non-equilibrium formulae are widely used. For successful application, the construction details of the wells used should be known; test pumping should be at a steady, unvarying rate and should be carefully measured; and water-level measurements should be accurately made and timed. Measurements of the recovering water-level after pumping has stopped have the advantage of not being affected by changes in pumping rate.

159. The modified non-equilibrium formula described by Jacob can be used to determine the coefficient of transmissibility from the data obtained while the well is being pumped or from the recovery data.[4] Bierschenk and Wilson described the practical application of the formula to field data obtained from pumping tests.[5] In commonly used units, Jacob's formula is as follows:

$$T = \frac{264\,Q}{s}$$

where:

T = coefficient of transmissibility, in gallons per day per foot,

Q = discharge of pumped well, in gallons per minute and

s = the drawdown difference per log cycle of t

(t = time since pumping started, or stopped, in minutes)

The coefficient of storage cannot be determined with any degree of accuracy from data for the pumped well because the effective radius of the pumped well is seldom known and drawdowns in the pumped well are often affected by well losses which cannot be determined precisely. Water-level measurements in one or more observation wells during a pumping test of long duration are necessary for accurately determining the coefficient of storage. Measurements of the water-level in observation wells in conjunction with pumping tests were not recorded during this project.

160. The results of the bailing tests, slug-injection tests and pumping tests are given in tables 10, 11, 12, 13, 18 and 19; and are shown in figures X, XI, XII and XIII.

161. The specific capacity of a well is its rate of yield per unit of drawdown and is determined in this report by dividing the yield, in gallons per minute, by the drawdown, in feet. The hydraulic properties of an aquifer may be estimated by the examination of well-log, water-level and specific-capacity data. Generally, high specific capacities indicate a high coefficient of transmissibility and low specific capacities indicate low coefficients of transmissibility. However, the specific capacity of a well often is only an approximate measure of the coefficient of transmissibility because specific capacity may be adversely affected by such factors as partial penetration, well loss, or incomplete well development. Also, under water-table conditions, the specific capacity of even a fully developed well is constant only when the drawdown is a small fraction of the saturated thickness of the aquifer. Although subject to the above limitations, rough estimates of coefficients of transmissibility are useful in a ground-water investigation.

162. A series of graphs given by Walton was used to estimate coefficients of transmissibility from specific capacities.[6] Coefficients of storage (S), which are necessary for the use of Walton's graphs, were not determined by pumping tests for the project area. However, estimates of S for water-table and artesian conditions were made from well-log and water-level data. That is, the water-level in each well was determined to be either unconfined or under artesian pressure. Because specific capacity varies with the logarithm of 1/S, large errors in estimated coefficients of storage result in comparatively small errors in coefficients of transmissibility estimated with specific-capacity data. The results of the estimates are given in table 10.

B. Kurnub sandstone

163. The loosely-cemented, fine-grained sandstone that comprises much of the Kurnub formation proved

[2] K. E. Anderson, *Water Well Handbook*, Missouri Water Well Drillers Association (Rolla, Missouri, United States; 1955), p. 133.

[3] Todd, op. cit., p. 90.

[4] C. E. Jacob, "Flow of Ground Water", *Engineering Hydraulics*, H. Rouse, ed. (New York, John Wiley and Sons, 1958), pp. 321 to 386.

[5] W. H. Bierschenk, and G. R. Wilson, *The Exploration and Development of Ground-Water Resources in Iran*, International Association of Scientific Hydrology, Pub. No. 57 (Athens, 1961).

[6] W. C. Walton, *Selected Analytical Methods for Well and Aquifer Evaluation*, Illinois State Water Survey, Bulletin 49 (Urbana, Illinois, United States; 1962), pp. 12 and 13.

Table 10

ESTIMATED COEFFICIENTS OF TRANSMISSIBILITY

Number of well	*Water yielding unit*[a]	*Type of test*[b]	*Specific capacity (gpm/ft)*	*Water-table or artesian*	*Coefficient of transmissibility (gpd/ft)*
AZ- 1	B 2	PT	5.5	A	12,000
AZ- 2	B 2	BT	1	A	1,500
AZ- 8	B 4	PT	10	WT	13,000
AZ-11	B 4	PT	700	WT	1,000,000+
AZ-12	V and B	PT	180	WT	300,000
AZ-15	B 4	BT	3	WT	2,000
AZ-19	B 5	BT	1	WT	1,000
PAB-12	Qal	BT	1	WT	600
Hammam No. 2	B	PT	5	WT	6,000
AG-3 (105-D)	B 4	PT	5	Art.	10,000

[a] Belqa Series and number of unit where known; V, volcanics; Qal, alluvium.
[b] PT, pumping test; BT, bailer test.
[c] Estimated from Walton, op. cit., pp. 12 and 13.

difficult to develop for a water-supply where it was penetrated by wells in the project area. Reportedly, an attempt to develop the formation for water in Safra No. 1 well failed when the sands caved into the hole. Caving of the formation also was encountered in well AZ-1 during drilling and clean-out operations. After the Belqa 2 artesian zone had been cased and cemented off in well AZ-1, the casing was extended to a depth of 1,295 metres (25 metres into the Kurnub) and a swabbing test was made. Water in the Kurnub formation here is under artesian pressure; at completion of the swabbing test, the water-level rose to 90 metres below land surface (1,145 metres above the top of the formation, its depth below land surface in the of the Kurnub formation in this well and although the aquifer was only partly penetrated and insufficiently developed, the test indicated that the formation has a low coefficient of transmissibility in this local area.

164. In addition to the apparently low permeability of the formation, its depth below low surface in the Azraq Basin is so great that drilling costs and excessive pumping lifts would make its development unfeasible under present economic conditions.

C. Ajlun Series

165. Limestones of the Ajlun Series form aquifers in other parts of Jordan; for example, in the Wadi Dhuleil area about 10 kilometres north-west of Qasr Hammam es-Sarhk and in the Wadi Abdun-Zarqa area near Amman (map 2). In most places where the formation yields water to wells, however, the ground water is contained in fractured and cavernous limestones where beds of relatively impermeable marl and shale form perched water-tables locally. Thus, the yields are limited by the capacity of the perched body of ground water and the size of the recharge area.[7] Wells AZ-1 and Safra No. 1 completely penetrated the Ajlun Series, but reportedly the formation was not water-bearing in either of these wells.

[7] Quennell, op. cit., and Brown Engineers, op. cit.

166. The little evidence that is available indicates that the limestones of the Ajlun Series are relatively unimportant as an aquifer in the project area. In the central and eastern part of the area the formation is at a considerable depth below land surface and the cost of exploring it for ground-water supplies probably would not be warranted. Near the north-western boundary, where the formation is at a shallower depth, small quantities of water might be obtained from perched ground-water bodies in the limestones.

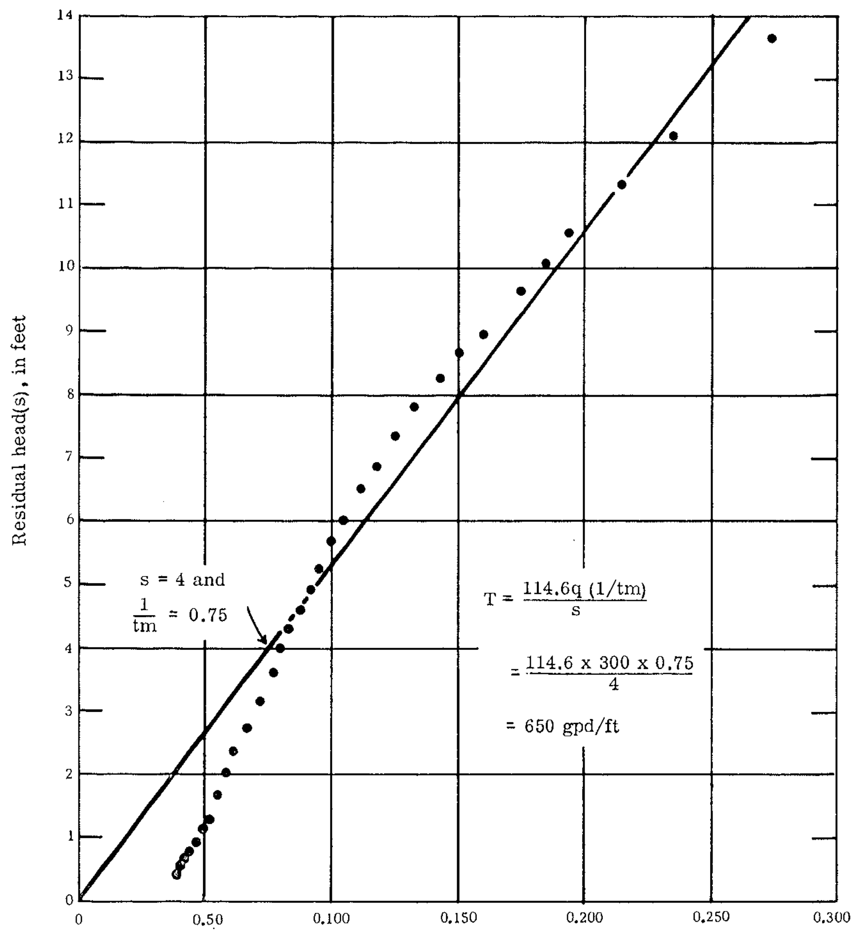
D. Belqa Series

167. According to Quennell, the Belqa formation receives recharge where it crops out within the project area (map 2) and in its outcrop area west of the Azraq Basin. Most of the test holes and wells in the project area tapped the formation; wells AZ-1 and Safra No. 1 penetrated its full thickness. The water-bearing properties of the formation vary widely with the physical characteristics of its different units; differences in thickness and permeability of the individual aquifers, and in well construction and development cause the specific capacities of wells to range from zero to large. Coefficients of transmissibility also have a wide range (see figures X to XII and table 10).

168. Of the five distinct units of the group that have been delineated on the basis of lithological characteristics, the B 1 unit has the least thickness and the poorest water-bearing properties. Wells AZ-1 and Safra No. 1 penetrated the unit and, reportedly, it was not water-bearing in either of these holes.

169. The B 2 unit was penetrated in wells AZ-1 and 2 and was water-bearing in both wells. A total thickness of 124 metres of chalk, limestone and chert of the unit was penetrated in well AZ-2. Estimates of the coefficient of transmissibility of the B 2 unit in well AZ-2 range from 650 gpd/ft for the slug-injection test (figure X) to 1,500 gpd/ft for specific capacity data (table 10), which indicates poor water-bearing properties for the unit in this vicinity.

Figure X. Slug-injection test curve for well AZ-2, B2 aquifer



Reciprocal of time in minutes since injection of slug $(\frac{1}{tm})$

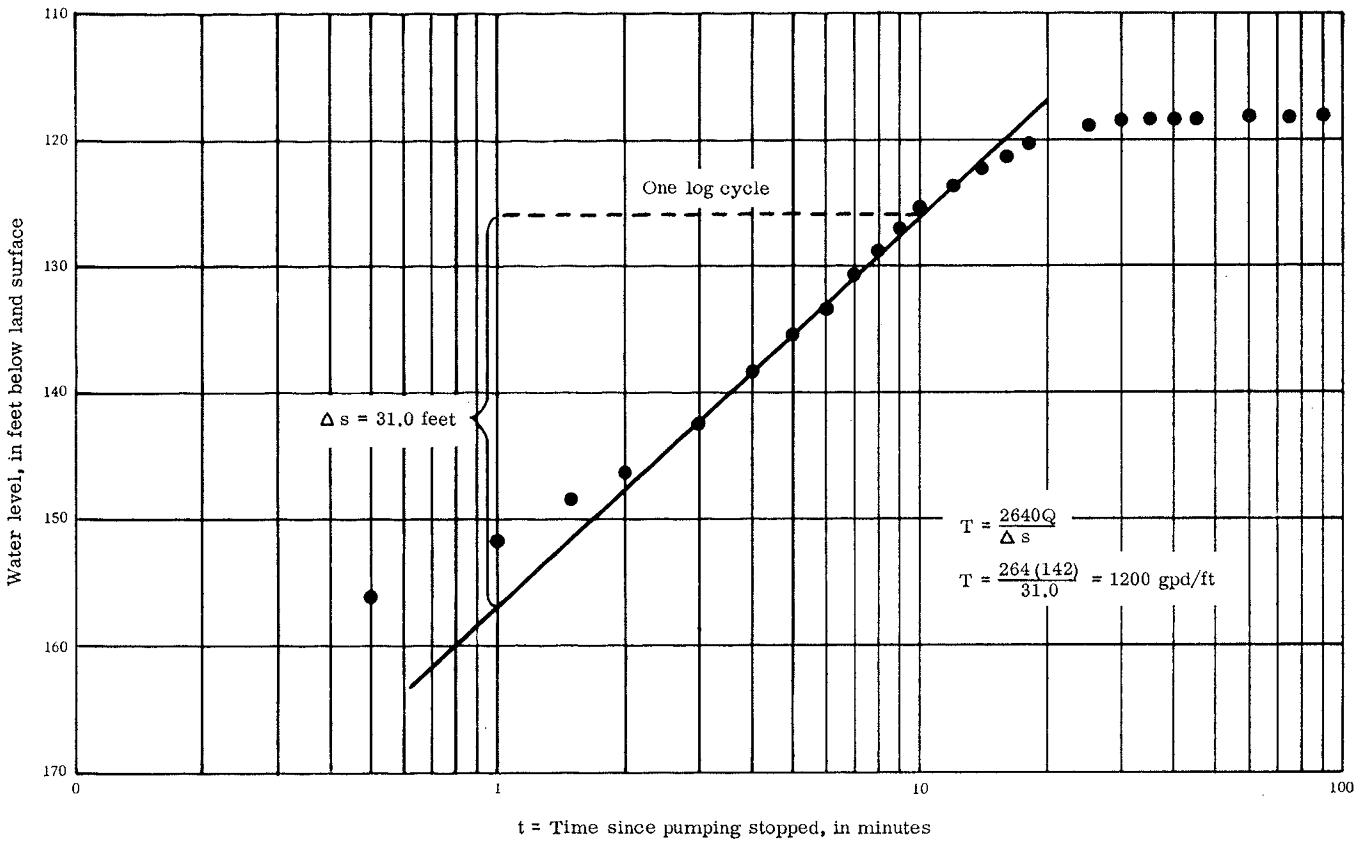
170. The thickness of 191 metres of the B 2 unit penetrated in well AZ-1 consists of interbedded limestone, sandstone, chert and marl. During drilling operations, the zone from 420 to 502 metres produced an artesian free flow at the land surface and continued to yield free flow after completion of the well. During 2-3 March 1964, two consecutive 24-hour pumping tests were made on the artesian aquifer (see chapter V). Pumping rates and drawdown measurements were too erratic to provide accurate enough data to compute the coefficient of transmissibility by the modified non-equilibrium method, so the average specific capacity for the two tests, about 5.5 gpm/ft, was applied to Walton's graphs. From this analysis, the coefficient of transmissibility for the B 2 artesian aquifer was estimated to be about 12,000 gpd/ft. In November 1964, the head valve on well AZ-1 was opened, the artesian head of the aquifer was measured at 22.8 feet above land surface and the free artesian flow was estimated at about 190 gpm.[8] The regional water-bearing characteristics of this artesian aquifer are poorly known, but the two pumping tests show that large quantities of water can be pumped from the B 2 artesian zone in the vicinity of well AZ-1.

171. The change in the water-bearing properties of the B 2 unit between wells AZ-2 and AZ-1 probably is owing to an increase in permeability and thickness of the unit in an easterly direction. Some of the ground water that has entered the B 2 aquifer at its outcrop area or by infiltration from overlying formations moves toward the centre of the Azraq Basin and is confined under impermeable beds so that it is under sufficient artesian pressure to flow at the land surface in well AZ-1. The confining beds probably are not wholly impermeable and they may allow upward leakage of some water that joins the ground water in the overlying units and helps to maintain the springs and seeps at El-Azraq.

172. The B 3 unit contained ground water in wells AZ-1, 3, 4, 5 and 23, and in well PA-4; in well AZ-1 the water was of very poor quality (see table 6). The

[8] Kamel A. Kawar, Jordanian Central Water Authority, in a written communication of December 1964.

Figure XI Recovery curve for well PA-4, B3 aquifer

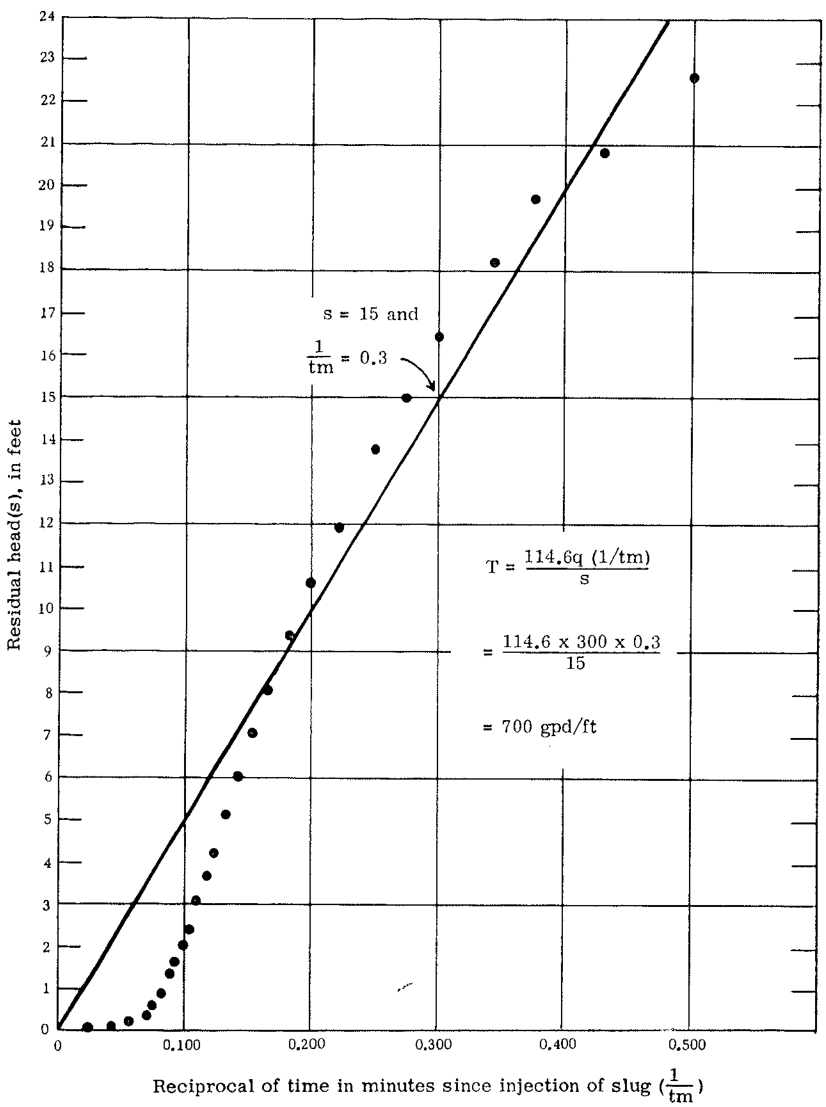


water-bearing properties of the unit were tested in wells AZ-23 and PA-4. A slug-injection test of well AZ-23 indicated a coefficient of transmissibility of about 700 gpd/ft. However, the plotted data from the test (figure XII) indicates insufficient well development and the well may not have penetrated the full thickness of the aquifer. Thus, the value for T gives the order of magnitude only. Recovery data from a pumping test on well PA-4 (figure XI) give a more accurate value for the coefficient of transmissibility, 1,200 gpd/ft. In this well, a thickness of 202 metres of the B 3 unit was penetrated. The ground water in both wells AZ-23 and PA-4 was under artesian pressure (see tables 19 and 20). In general, the unit has poor water-bearing properties and only yields water locally from the limestones. The marls and shales of the B 3 unit function chiefly as a semi-aquiclude, which helps to maintain artesian pressure in the underlying units.

173. The B 4 unit contained ground water in wells AZ-1, 8, and 15; PA-3 and 5; PAB-14, 15, 17; AG-3 (105-D); 103-B; and 104-C. Well AZ-11 was test pumped for 24 hours at a rate of 700 gpm with a maximum drawdown of only one foot, which would give a specific capacity of 700 gpm/ft and an estimated coefficient of transmissibility of over 1 million gpd/ft. Such values are unusually high and generally would be found only in formations such as cavernous limestone or interflow zones in basalts. However, during their test-drilling programme, Baker-Harza (1958) reported striking a cavity in well PA-6, which contained abundant ground water. No log is available for well PA-6, but the large specific capacity of well AZ-11, which is only 1.5 kilometres south of well PA-6, suggests that abundant quantities of ground water may be contained in solution cavities in the chalk and limestone locally. Estimates of the coefficient of transmissibility from specific capacities for other wells that produce from the B 4 unit ranged from 13,000 gpd/ft for well AZ-8 to only 2,000 gpd/ft for AZ-15 (table 10). Thus, the water-bearing properties of the unit vary from poor to excellent. The unit crops out over a large part of the project area (see map 2) and offers a large catchment area for recharge. However, the quantity of water available in the unit in any one place probably depends on the extent of jointing and solution cavities in the limestones and chalks. In some places, recharge from the land surface or the overlying basalt may be restricted by the absence of jointing or by the joints being filled with impermeable weathered material. Part of the ground water in the unit near the central part of the basin probably is derived from water that rises by upward leakage from underlying artesian aquifers.

174. Data on the water-bearing properties of the B 5 unit are scanty. Well AZ-19 produces from the B 5 unit and is used as a desert watering point. The well

Figure XII Slug-injection test curve for well AZ-23, B3 aquifer



was bailer-tested for only 1/3 of an hour, which is too short a time for reliable estimates of specific capacity. However, application of the specific capacity of 1 gpm/ft to Walton's graphs indicates a coefficient of transmissibility of about 1,000 gpd/ft in the vicinity of well AZ-19. The B 5 unit contained water in test holes P-1, 3 and 6, but data on specific capacity are not available. Indications are that the unit is not important as an aquifer, but that it does conduct some ground water westward toward El-Azraq (see map 4). Recharge enters the unit where it crops out at the land surface and where it is overlain by basalt (see map 2).

175. In addition to the perennial supply of ground water discharged at El-Azraq (see paras. 93-123), a large volume of water is stored in the Belqa formation, especially in the B 2, B 3 and B 4 units. Available hydrogeological data are not adequate to accurately determine the quantity in storage, but there is every indication that it is sufficient to meet emergency future requirements for a period of many years.

E. Volcanics

176. The volcanics that crop out over the northern part of the project area consist mainly of basalt flows with some intercalated beds of ash and clay. In much of that area, the basalt apparently serves as a medium for recharge by permitting ground water to percolate downward through vertical joints and into the underlying Belqa formation. Locally, however, where the basalt flows fill pre-existing valleys in the Belqa formation and are below the water-table, and where beds of clay form perched bodies of ground water, the volcanic rocks yield water to wells. In his communication of December 1964, Mr. Kawar stated that Tapline 6-A well, which penetrates only basalt, yields 57 gpm for

Table 11

SLUG-INJECTION TEST DATA FOR WELL AZ-2 B2 AQUIFER—TESTED 17 JANUARY 1964

(Pre-injection water level below land surface=234.05 feet,)
(300-gallon slug of water injected at 0 minutes)

Time after slug (minutes)	*Residual head (feet)*	*1/tm (1/min)*	*Time after slug (minutes)*	*Residual head (feet)*	*1/tm (1/min)*
0	0	0	11.00	4.90	0.091
3.67	13.63	0.273	11.50	4.60	.087
4.25	12.10	.235	12.00	4.29	.083
4.67	11.35	.214	12.50	3.97	.080
5.16	10.53	.194	13.00	3.60	.077
5.50	10.05	.184	14.00	3.15	.072
5.75	9.62	.174	15.00	2.73	.067
6.25	8.92	.160	16.00	2.37	.062
6.67	8.65	.149	17.00	2.02	.059
7.00	8.25	.143	18.00	1.67	.056
7.50	7.80	.133	19.00	1.29	.053
8.00	7.31	.125	20.00	1.13	.050
8.50	6.88	.118	21.00	0.95	.048
9.00	6.46	.111	22.00	0.77	.045
9.50	6.00	.105	23.00	0.66	.043
10.00	5.67	.100	24.00	0.54	.042
10.50	5.23	.095	25.00	0.45	.040

10 hours each day the year round. Well AZ-12 penetrated 57 metres of basalt (with intercalated beds of clay) and 198 metres of the Belqa formation. A pumping test on this well indicated a specific capacity of 180 gpm/ft and an estimated coefficient of transmissibility of 300,000 gpd/ft, but it is not clear from the record of the well whether the principal aquifer is in the basalt or the Belqa formation. Well H-5 No. 1 also penetrates both the basalt and the Belqa, but here again it is not clear which formation contains the aquifer. The basalt contains water in both wells Hababiya No. 1 and No. 3. In order to determine the water-bearing properties of the basalt, further exploration by drilling and testing would have to be done.

F. Plateau group

177. The plateau group has not been sufficiently explored to determine its water-bearing properties in the project area. In their draft report of 1964, Hunting Technical Services Ltd. reported that the formation yielded water to wells in the Wadis Sayih, Zarqa, and Dhuleil, which are west of the Azraq Basin in an area of higher precipitation. Where the formation is exposed in the project area, precipitation is low and thus, recharge will be low. The formation probably acts mainly as a medium of recharge to the underlying rocks and in some places may contain perched bodies of ground water.

G. Alluvium

178. The alluvium contained water in wells AZ-9, PAB-12, Shomari No. 1 AG-1 (101), I-29 and I-41. Specific capacities are not available for wells AZ-9, I-29 and I-41. The water in well AZ-9 increased in salinity as the well was bailed (see paras. 131-142). The coefficient of transmissibility estimated from the specific capacity for well PAB-12 was only about 600 gpd/ft. Plotted data from a pumping test on Shomari No. 1 well indicate a coefficient of transmissibility of 70,000 gpd/ft (figure XIII). Although Shomari No. 1 well has a relatively high specific capacity, the quality of the water was deteriorating during 1963 (see table 7). Water is withdrawn from the alluvial deposits through some additional shallow hand dug wells in and near Qá El-Azraq for domestic and irrigation use, and some for salt production. Available data indicate that the water-bearing properties of the alluvium vary widely, but generally are poor.

V. DRILLING OPERATIONS

A. Previously drilled wells

179. Production and test wells had been drilled throughout the Azraq Basin prior to the beginning of the project on which this report is based. Their locations, including the wells and test holes drilled during this project, are shown on map 2. Available basic data on selected wells in the project area are given in tables 18 and 19. Geological columns, electric logs and gamma-ray logs of three wells are shown in figure XV (in pocket).

180. Safra No. 1 is an abandoned exploratory well drilled by the Pauley Oil Co. in 1958. It penetrated the entire sedimentary section and bottomed in the granitic basement complex at 2,582 metres. Water was reported in the Kurnub formation from approximately 915 to 1,080 metres and upon termination of the oil company's activities, some investigations of water potential were carried out by Baker-Harza and by personnel of FAO. The hydrostatic water level was 366 metres below land surface and the water was of sodium chloride type with about 1,800 ppm total dissolved solids. There was some question whether the bore hole had been completely freed of drilling fluid during the bailing; but because bailing was carried out (although apparently intermittently) for 2 weeks and the water quality reached a fairly constant composition, it is believed that the figures obtained were probably fairly accurate.

181. The Mayhew standard-rotary drilling rig was moved over this well in October 1962 for clean-out and further testing, and to give the crew training on the equipment prior to undertaking regular drilling operations. An obstruction, first thought to be a bridge, was

Table 12

RECOVERY DATA FOR WELL PA-4, B3 AQUIFER —TESTED 27 FEBRUARY 1964

(Pre-test water-level below land surface=117.95 feet,)
(average pumping rate—Q=142 gpm)

Time since pumping stopped t *(minutes)*	*Measured depth to water (feet)*	*Recovery* s *(feet)*	*Time since pumping stopped* t *(minutes)*	*Measured depth to water (feet)*	*Recovery* s *(feet)*
Pumping	stopped		12	123.55	5.60
0.5	156.05	38.10	14	122.20	4.25
1	151.58	33.63	16	121.25	3.30
1.5	148.43	30.48	18	120.34	2.39
2	146.15	28.20	20	119.90	1.95
3	142.38	24.43	25	119.00	1.05
4	138.30	20.35	30	118.55	0.60
5	135.48	17.53	35	118.39	0.44
6	133.22	15.27	40	118.37	0.42
7	130.83	12.88	45	118.33	0.38
8	128.81	10.86	60	118.23	0.28
9	126.90	8.95	75	118.13	0.18
10	125.40	7.45	90	117.94	+0.01

Table 13

SLUG-INJECTION TEST DATA FOR WELL AZ-23 B-3 AQUIFER—TESTED 11 MARCH 1964

(Pre-injection water level below land surface=267.75 feet)
(300-gallon slug of water injected at 0 minutes)

Time after slug (minutes)	*Residual head (feet)*	*1/tm (1/min)*	*Time after slug (minutes)*	*Residual head (feet)*	*1/tm (1/min)*
0	0	0	7.50	5.1	0.133
2	22.6	0.500	8.00	4.23	.125
2.33	20.8	.430	8.50	3.67	.118
2.67	19.7	.375	9.00	3.12	.111
2.92	18.25	.342	9.50	2.40	.105
3.33	16.43	.300	10.00	2.01	.100
3.67	15.04	.273	10.50	1.65	.095
4.00	13.74	.250	11.00	1.45	.091
4.50	11.98	.222	12.00	0.89	.083
5.00	10.59	.200	13.00	0.58	.077
5.50	9.41	.182	14.00	0.38	.072
6.00	8.10	.167	17.00	0.21	.059
6.50	7.07	.154	23.00	0.10	.043
7.00	6.05	.143	37.00	0.05	.027

struck at 361 metres during the clean-out. However, after drilling out 139.7 metres of rocks and sand, it was concluded that the well must have caved and filled, and that the cost and time involved in the clean-out were not warranted. The project was therefore abandoned and on 21 November the move to well AZ-1 was commenced.

B. Deep test well AZ-1

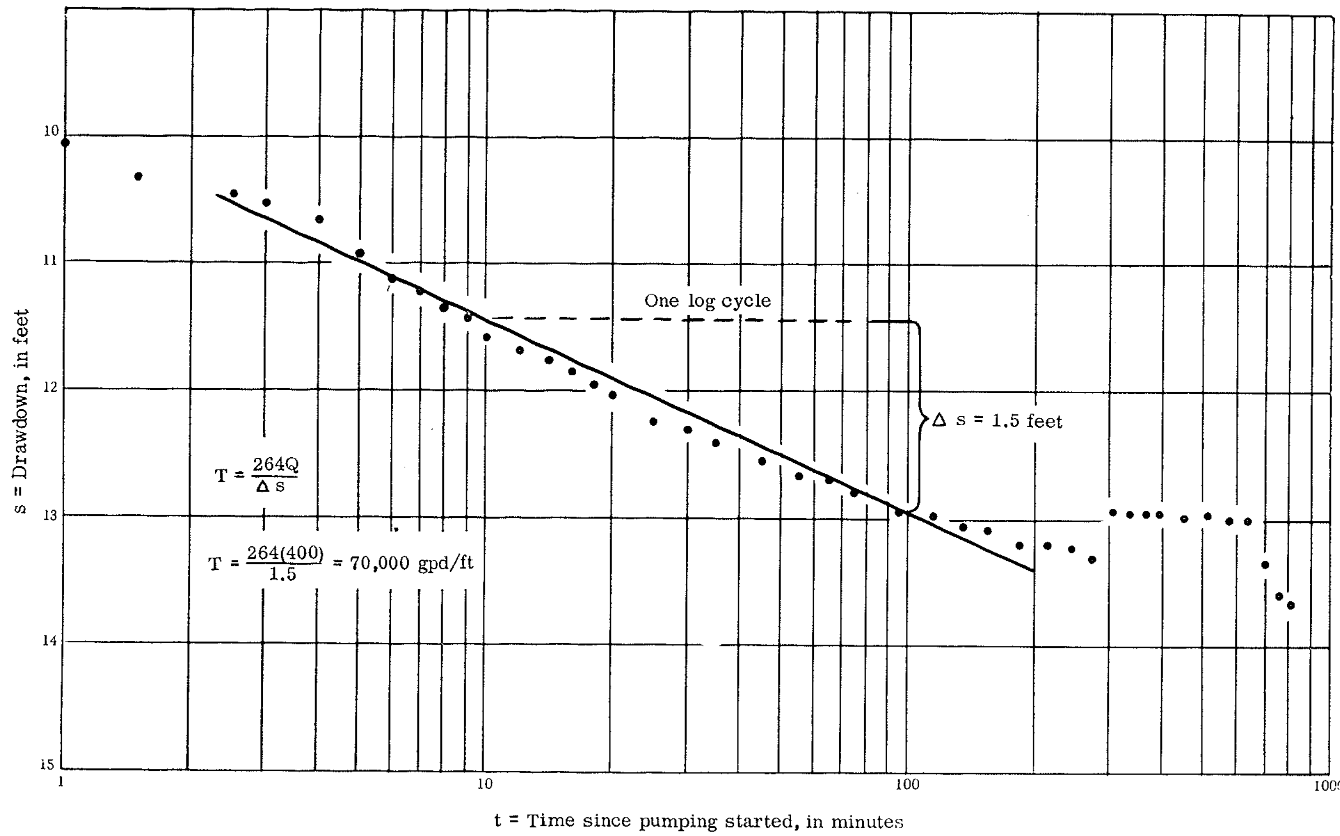
182. Well AZ-1, the test hole for exploration of the deeper aquifers, was spudded in on 4 September 1962 with a CWA cable-tool drilling rig and drilling by cable tool reached a depth of 186 metres by 25 November. On 28 November, the Mayhew rotary drilling rig was moved over the hole and 16-inch casing was set to 52.7 metres, with perforations between 26.8 and 45.9 metres. Then, 13-3/8-inch casing was installed and cemented with the shoe at 186.0 metres.

183. Rotary drilling was started on 23 December on a two-shift basis. An 8-3/4-inch hole was drilled to 275 metres, then reamed to 12-1/4 inches. From 275 metres to 322 metres, the hole was drilled to a full 12-1/4-inch diameter. A small quantity of saline water (50,000 ppm total dissolved solids, see table 6) was found between 235 and 322 metres, but circulation was not lost and, after stopping for a bailing test and electric logging, drilling was resumed.

184. Indications were that an aquifer was being penetrated at 420 metres, so on 4 March 1963, 9-5/8-inch casing was installed and cemented at 420.4 metres. The cement plug was drilled out with an 8-3/-inch bit and the hole was drilled 0.20 metres deeper. Drilling operations were shut down during the night and in the morning water under artesian head was flowing from the well; the artesian head was measured at 25.6 feet above land surface. The water was displaced with drilling mud and drilling was continued to 424 metres, where circulation was lost completely. Drilling was continued to 426.3 metres without returns. A 20-sack cement plug was placed in this zone, but was not effective in sealing the leak. Drilling was resumed, circulating water, with the artesian flow gradually increasing as drilling progressed. Between 456.6 and 458.3 metres, drilling was very slow and difficult due to the hardness of the formation, and required six Hughes CWC bits (a bit cost of US $650 per metre).

185. When the well had reached a depth of 458.8 metres, a pumping test was made on 24-26 March 1963. The pre-test artesian head was 22.3 feet above land surface. The well was pumped for 48 hours at a rate of 225 gpm with an average drawdown of about 39 feet below land surface (total drawdown, 22.3 + 39 feet = 61.3 feet). Upon completion of pumping, the water-level recovered its pre-test artesian head in 8 minutes. Drilling was then resumed and progressed with relative ease to 503 metres. At this depth the formation became extremely hard, and it was necessary to drill a 6-1/4-inch pilot hole and ream to 8-3/4 inches. Drilling and reaming continued to 522 metres where a twist-off of the drill string occurred. However, the fish was recovered the same day and drilling was resumed. At 552.9 metres, drilling was continued with 6-1/4-inch bits because the stock of 8-3/4-inch bits had been temporarily exhausted. This pilot hole was carried to 587.7 metres and then reamed with re-tipped under-guage 8-3/4-inch bits and from 571.0 metres with new 8-1/2-inch W7RJ bits. On 2 June the rig was shut down for repairs to the traveling-block bearings. Following these repairs, work was resumed on 10 June on a three-shift basis and performance was much improved. The receipt of six new 7-inch drill collars on 16 June gave the additional weight necessary for optimum penetration. At 610 metres the chert content of the formation increased again, which greatly reduced bit life. This hard drilling continued, with some soft breaks, to 714 metres, where drilling conditions improved markedly.

Figure XIII Drawdown curve for Shomari No. 1 well, AG-1 (101), Alluvium



186. On 19 July a depth of 834 metres was reached, an electric log was made and 6-5/8-inch casing was installed to 834 metres. Drilling then was continued, using 5-5/8 and 5-7/8-inch bits. Progress was rapid and uneventful, and the Kurnub sandstone was entered at 1,255 metres. On 11 September, with the total depth a 1,297 metres, the drill string was struck by formations caving from above. Circulation was maintained, however, and by substituting crude oil for mud, the string was freed. In view of the caving conditions, it was decided not to attempt any further drilling, so the hole was cleaned, total depth was established at 1,299 metres and an electric log was made.

187. Quality and temperature studies indicated leakage around the 6-5/8-inch casing shoe, and during 19-26 September the suspected leak was successfully sealed by a cement squeeze. In order to test the Kurnub formation, 402 metres of 4-1/2-inch casing were hung on the end of a string of drill pipe, which placed the bottom of the 4-1/2-inch casing at 1,275 metres. A swabbing test was made and samples of the water were collected for chemical analysis. The artesian pressure head of water in the Kurnub formation was measured at 90 metres below land surface. A slug-injection test was made and the 4-1/2-inch casing was pulled. The 6-5/8-inch casing was cut at a depth of 502 metres and the upper part pulled, leaving 6-5/8-inch casing between 502 and 834 metres. The 9-5/8, 13-1/2 and 16-inch casing strings were left intact in the well. Thus, the well was left uncased between 420.4 and 502 metres, and between 834 and 1,299 metres. At land surface, the casing was fitted with a shut-in head, a pressure gauge and a valved 2-inch discharge pipe. Construction operations on the well were completed on 12 December 1963. Additional pumping tests were made on the Belqa 2 aquifer during 2-3 March 1964. The pre-test artesian head was 24 feet above land surface. During the first 24-hour test, the well was pumped at an average rate of 635 gpm with a maximum drawdown of about 114 feet. Then the pump was stopped for 7 minutes for servicing. During the following 24-hour test the pumping rate averaged 650 gpm with a maximum drawdown of about 124 feet. The water-level recovered to its pre-test artesian head 20 seconds after the pump was stopped.

188. The costs of drilling well AZ-1 are given in table 15. The total cost (excluding office overhead, depreciation and expatriate supervision) of US $122,611.29 seems very high. This should be reduced on another well by the use of a three-shift operation throughout and by the availability of the necessary weight in drill collars. Also, there were additional expenses for the construction of pipe racks, the doghouse, and similar items that would not be duplicated

Table 14

DRAWDOWN DATA FOR SHOMARI NO. 1 WELL, ALLUVIUM—TESTED 8 FEBRUARY 1964

(Pre-test water level below land surface=31.25 feet,)
(average pumping rate—Q=400 gpm)

Time since pumping started t (*minutes*)	*Measured drawdown* s (*feet*)	*Time since pumping started* t (*minutes*)	*Measured drawdown* s (*feet*)
0	0	65	12.70
1	10.06	75	12.80
1.5	10.32	85	12.83
2.5	10.48	95	12.95
3	10.53	115	12.98
4	10.66	135	13.05
5	10.93	155	13.09
6	11.10	185	13.20
7	11.22	215	13.18
8	11.35	245	13.23
9	11.45	275	13.31
10	11.59	305	12.93
12	11.69	335	12.95
14	11.75	365	12.95
16	11.85	395	12.95
18	11.95	455	12.98
20	12.03	515	12.95
25	12.24	575	12.99
30	12.30	635	12.98
35	12.41	695	13.36
45	12.54	755	13.59
55	12.68	815	13.65

Table 15

SUMMARY OF EXPENDITURES FOR WELL AZ-1

Item of expenditure	*Cost per item* (*JD*)
Contract cable-tool drilling (CWA)...........	1,019.079
Technical staff (local)........................	1,226.250
Skilled and unskilled labour..................	11,157.539
Fuels, oils, lubricants........................	9,843.678
Drilling materials...........................	16,016.327
Miscellaneous...............................	877.305
Total JD	40,140.178
Total US $	112,392.50

Cost per metre JD 30.901 } For a total depth
Cost per metre US $86.52 } of 1,299 metres

Casing left in well AZ-1

Diameter (*inches*)	*Length* (*feet and inches*)	*Price* (*US $ per foot*)	*Total Price* (*US $*)	
13⅜	610-2	5.32	3,246.08	
9⅝	1,379-1	3.35	4,619.93	
6⅝	1,089-3	2.16	2,352.78	
				10,218.79
		Grand total US $		122,611.29

Note: This does not include office overheads, cost of expatriate experts or depreciation of equipment.

on another well. However, when the items excluded in the AZ-1 costs are considered and when allowance is made for the extra depth that would be required for proper penetration of the Kurnub, it is probable that the cost per well could not be brought below the level of US $100,000.

C. Project Drilling Programme

189. The shallow exploratory drilling programme was started in September 1962 with two Bucyrus-Erie Model 60-L cable-tool drilling rigs contracted from the Central Water Authority. In January 1963 a third cable rig was obtained on contract from the Authority. A fourth rig was obtained from a commercial contractor and was in service for the project from 23 March to 15 June 1963. In May 1963 one of the Central Water Authority's rigs was transferred and in early July another of the rigs was replaced by a smaller model. The shallow-drilling programme was completed in November 1963. Eighteen of the AZ series of wells were drilled, ranging in depth from 50 to 301 metres, for a total of 2,514 metres in 30 rig-months. Thus, the average performance was 64 metres per rig-month. A summary of wells drilled and costs is given in table 16. Standard charges for drilling, by both the Central Water Authority and the contractor, were JD 8.000 (US $22.40) per metre for the first 100 metres, JD 10.000 (US $28.00) for the 100-to-200-metre interval,

Table 16

DRILLING COSTS FOR AZ SERIES OF WELLS

No. of well	*Depth* (*metres*)	*Cost per well* (*JD*)
AZ- 1WW	50	67.672
AZ- 2	163	512.737
AZ- 3	181	960.505
AZ- 4	202	939.670
AZ- 5	131	1,093.130
AZ- 8	94	748.000
AZ- 9	69	602.000
AZ-10	116	960.000
AZ-11	88	704.000
AZ-12	255	2,863.000
AZ-13	55	440.000
AZ-14	300	3,000.000
AZ-15[a]	54	432.000
AZ-19[a]	301	2,820.000
AZ-21[a]	90	720.000
AZ-22	79	632.000
AZ-23	124	1,040.000
AZ-29	162	1,420.000
	2,514	19,954.714
	Total US $	55,873.20

Cost of casing used in cable-tool drilled wells

(*US $*)

21 metres of 12-inch..................	340.00	
21 metres of 13⅜-inch.................	361.76	
23.64 metres of 13⅜-inch.............	409.64	
53.98 metres of 9⅝-inch..............	592.95	
Total		1,704.35
Grand total US $		57,577.55

[a] Commercial contract, A. H. Arekat.

and JD 12.000 (US $33.60) for the 200-to-300-metre interval. Casing and testing are not included in these prices. Well AZ-1 WW was drilled as a base camp water-supply well. The remainder were drilled for structural control, water-quality assessment and geohydrologic information. Two wells, AZ-19 and AZ-23, are to be fitted by the Authority as desert watering points and a pump had already been installed in well AZ-19. Also, well AZ-12 possibly could be used as a production well at some time in the future.

190. A series of 11 slim-hole observation wells were drilled with the Portadrill air-rotary rig during January and February 1963. Eight of these reached the water-table and were completed with 2-inch inside diameter casing. The total drilling amounted to 77.5 metres. A summary of these wells is given in table 17.

Table 17

SMALL-DIAMETER TEST-HOLE DRILLING PROGRAMME

No. of well	*Depth (metres)*	*Depth to water (metres)*	*Remarks*
P- 1	6.0	3.80	Cased
P- 2	14.0	—	Abandoned, too deep for compressor
P- 3	11.0	7.30	Cased
P- 4	4.0	2.25	Cased
P- 5	6.0	2.10	Cased
P- 6	8.0	2.95	Cased
P- 7	6.5	3.07	Cased
P- 8	4.0	—	Abandoned, caving
P- 9	4.0	—	Abandoned, caving
P-10	5.0	0.24	Cased
P-11	8.0	1.19	Cased
Total	77.5[a]		

[a] For 11 wells.

VI. AGRICULTURAL SURVEY

A. Soils

191. Soil studies made during the project were confined to the areas close to the springs, to Wadi er-Ratam and to Wadi esh-Shomari, because it became evident early in the investigation that the available resources were insufficient to justify long canals to transport the water to distant areas for irrigation use. Rather extensive classification data including detailed classification of 70,084 donums in the Wadi al-Butm area and 2,849 donums in Wadi er-Ratam are given in the Baker-Harza report previously cited. A detailed study of the lower Wadi er-Ratam area was made by F. Grünberg and F. Z. Dajani.[1]

192. Apart from the closed centre of the basin, the beds of wadies and the scattered mud flats, most of the Azraq soils are typical desert soils covered with pieces of flint and coarse pebbles. This type of soil is usually very shallow because of the slow process of the weathering action owing to the low rainfall. Plant life is deficient, and nitrogen and organic matter are lacking in the soils. Grünberg and Dajani stated that, "The erodibility of the soils in the Azraq area is very high. Due to the impermeable surface crust, rain, which often occurs as heavy rainstorm does not penetrate the soil. Heavy runoff and soil deterioration is the result."[1]

193. To improve such soils to the state where the farms would be self-supporting, the following steps would be necessary:

(a) Installation of proper drainage systems for washing down the salts, through irrigation with sufficient water;

(b) Use of farmyard manure plus a chemical fertilizer, probably superphosphate;

(c) Growing some cover-crop and ploughing it into the soil as green manure.

194. The irrigation agronomist inspected 13 soil pits along the upper Wadi er-Ratam, which covered an area of approximately 20 square kilometres. In this area, 5,000 donums were inspected and about 2,000 donums were found suitable for irrigation development, provided that suitable precautions and control measures are taken, such as provision for suitable drainage, proper use of fertilizer, selection of the right kind of crops and proper management of water.

B. Leaching and drainage

195. Irrigation is the application of water to cultivated lands in order to provide favourable conditions for the growth and development of plants. A successful irrigation scheme involves not only supplying irrigation water to the land, but also taking necessary precautions against salinity and alkalinity in the soil and irrigation water. The quality of irrigation water, irrigation practices and drainage conditions are very important in the control of salinity and alkalinity. Leaching of soil is the process of dissolving and transporting soluble salts by the downward movement of water through soil; and because salts move with water, reduction of salinity is directly dependent upon proper irrigation, leaching and drainage practices.

196. In order to establish an efficient irrigation scheme, the soils that are initially saline require the removal of the excess salts by addition of an adequate supply of irrigation water and may also require chemical amendment, such as gypsum. On the other hand, soils that are initially non-saline may become unproductive if excess soluble salts or exchangeable sodium are allowed to accumulate because of improper irrigation and soil management practices or inadequate drainage.

[1] F. Grünberg and F. Z. Dajani, "The Soils of Lower Wadi er-Ratam (Azraq Area)", typewritten report (Amman, 1963).

197. In the central playa of Qá Azraq the water-table is near the land surface in most places. The sub-soil water in many localities is extremely saline and may contain as much as 245,000 mg/litre of total soluble salts, much of which is sodium chloride. Also, this central portion of the basin is a topographical depression and there is no surface outlet for water draining into the area. All these factors would make reclamation a major project. However, the soils of some of the fringe areas are not very salty, the water-table is not dangerously high and many of these soils are gypsiferous.

198. Because most of the Azraq soils are saline, development of these lands by irrigation would be a difficult task, particularly if the irrigation water is also salty. The general principles of salt control are: (a) use of irrigation water with as low a salt content as possible; (b) maintenance of the ground-water level at least 2 metres (and preferably deeper) below the soil surface; and (c) flushing of accumulations of soluble salts from the surface soil.

199. The higher the salt content of the water, the lower the rainfall and the more impermeable the soil, the more difficult the problem of eliminating these salts becomes. Permeable soils in areas where winter rainfall is 250 millimetres lose most of the salts they accumulated in the summer. But flushing down salts with salty irrigation water in impervious soils presents many difficulties because this flushing must be done frequently; and during the process the soil is waterlogged, so that evaporation is rapid and any crops growing on the land suffer from poor aeration. Further, the higher the salt content of the water, the greater is the proportion of the water that must be used for flushing and the smaller is the proportion that the crops can use for transpiration. Increasing salinity reduces the efficiency of the water used.

200. The quantity of water needed for flushing down salts also can cause administrative difficulties because 1/4 to 1/3 of the water entering the area must be used solely for washing down the salts and not for crop growth; consequently, the maximum area that can be irrigated must be reduced by this fraction. This is true for the Azraq area; and assuming that in other parts of Jordan, under normal circumstances, 1 donum of land requires 500 m^3 per two cropping seasons, then about 1,500 m^3 per two seasons are required in the Azraq area. These figures are only approximate because the duty of water has not been established exactly for the Azraq area.

C. Existing farms and pilot farm

201. There are about twelve small farms in the Azraq area, ranging in size from 1 to 25 acres. Among the largest and the most successful are the Shomari Government Farm and the Sheshan Farm of Said Ghanim (see map 3).

202. The area at Shomari demarcated for possible development by the Government is 5,500 acres. It is part of the Wadi esh-Shomari area and, in general, contains the best soils of the whole Azraq area. However, the area actually put under irrigation agriculture so far is only 25 acres. The irrigation agronomist, after a visit to the Shomari Farm in January 1963, reported that conditions there were disappointing. According to him, the crops had not been weeded and uncontrolled parasites were destroying the crops. Upon asking the reason for the negligence, he was told that the farm was originally intended only to grow fodder crops to feed government livestock, and not food crops for human consumption. The agronomist felt that the careless farming methods set a poor example to individual native farmers who were trying to develop small plots of land. However, after a second visit to the Shomari Farm in April 1963, the agronomist reported that it had been weeded and that the crops looked healthy, especially the wheat, barley, clover, onions and broad beans. Although the Shomari Farm is situated on the best soils of the area, composed of salt-free, deep silty loam, the water from Shomari No. 1 well is not of very favourable quality for irrigation (see table 6). There are also indications that the salt content of the water is increasing, probably due to the influence of return water from irrigation (see table 7).

203. The Said Ghanim Farm at Sheshan Village was started with 1.5 acres of land, but the owner has been extending the farm area by leaching the soil for the last 10 years and he now has 4 acres. The farm lies on the north edge of Sheshan Village, approximately 150 metres west of the north pool of the Sheshan Springs. The soils of the farm are composed of alluvial and lacustrine deposits. The western half of the farm consists of alluvially deposited loams and silt loams with intermixed gravels, with the gravels becoming more abundant at a depth of 30 centimetres. The water apparently has remained stable at a depth of about 2 metres inasmuch as the area reclaimed 10 years ago has remained productive. The salinity content of these soils prior to leaching was in excess of 3 per cent; at present it ranges from zero to 0.20 per cent. All reclamation practices have used only natural drainage facilities. In the eastern half of the farm, which is underlain by relatively heavy clay soils composed of lacustrine deposits, the water table is 0.75 metres below the land surface. The leaching of excessive salts in these soils has not been successful. Installation of proper drainage facilities is very essential for the reclamation of this part of the farm, but the nearness of the area to the Sheshan pools and adjacent marshes makes such measures unfeasible.

204. Preliminary plans were made to establish a pilot farm in the Azraq area and the land was actually selected and prepared for manuring, ploughing and putting under winter crops. The site which was selected lies 2 kilometres north-west of Sheshan Village on the right bank of Wadi er-Ratam. The total area is

15 acres and initially it was planned to develop half of it by irrigation from well AZ-11, which is only 691 metres west of the farm area. The highest point on the farm is 514.40 metres and well AZ-11 is at an elevation of 520.77 metres. A general farm budget was prepared for the pilot farm. The total estimate of JD 10.316 (equivalent to US $28,884.80) was allocated as follows:

- (a) Investment in pumping plant, machinery and buildings, JD 4.964;
- (b) Allocation for fixed charges, JD 746;
- (c) Allocation for annual operating costs, JD 4.606.

Note that the capital investment is almost equal to annual expenditure.

205. The following crops were recommended as suitable for conditions at Azraq:

- (a) Grains:
  - (i) Winter crops: wheat and barley;
  - (ii) Summer crops: sorghum and maize;
- (b) Vegetables:
  - (i) Winter crops: onions, cabbage, cauliflower and peas (garden);
  - (ii) Summer crops: cucumber, eggplant, marrow and potatoes;
  - (iii) Summer and winter crops: broad beans and tomatoes;
- (c) Commercial and industrial produce:
  - (i) Winter crops: sugar-beets;
  - (ii) Summer crops: peanuts, sesame and cotton;
- (d) Fruits (summer crop): water-melons and other melons;
- (e) Fruit trees: date palm, grape, olive and fig;
- (f) Feed crops:
  - (i) Winter crop: mangel;
  - (ii) Winter and summer crops: clover, alfalfa and cow peas.

206. With the decision to phase out the project, all work on the pilot farm was discontinued.

207. In summary, the high salinity of most of the soils in and adjacent to El-Azraq and the shortage of ground water of sufficiently good quality to leach out the salts make any large expansion of irrigation agriculture unfeasible. The salinity of most of the soils is higher than even salt-resistant plants can tolerate, and only very small areas are suitable for reclamation. The soils on many of the higher areas are too thin to be suitable for agriculture.[2]

[2] Grünberg and Dajani, *ibid.*

VII. MUNICIPAL WATER-SUPPLY POTENTIAL

208. Aside from irrigation application, other proposals for the utilization of Azraq water have been made. The most significant of these, contained in a report by Brown Engineers International, Inc., is a discussion of the possibility of exporting water from the basin to supplement the Amman municipal supply. They suggested that the project might be feasible in the future, but that it would increase water-rates to around 100 fils per cubic metre. Although the new municipal wells have relieved the immediate shortage in Amman, potential future needs both there and in other parts of the country should be taken into consideration.

209. In Brown Engineers' analysis of the utilization of Azraq water, a pipeline length of 95 kilometres with 200 metres lift was assumed, with pumping rates ranging from 250 to 2,000 m^3/hr. Because it has been estimated that the net recoverable water from the basalt-shield area will not exceed 1,000 m^3/hr, only rates of 750 and 1,000 m^3/hr are considered in this report. A tabulation of costs is given in table 18. These are modified from Brown Engineers' report; with an upward adjustment of 10 per cent on material costs and 20 per cent on salary and maintenance costs, to reflect changes over the past 4 years. An additional analysis of 20-inch pipe of 750 m^3/hr indicates that 24-inch pipe is the preferred size for this pumping rate. The costs per cubic metre do not include treatment, storage, or distribution. Treatment would consist only of chlorination.

210. Present water-charges in Amman are 45 fils per cubic metre up to 12 cubic metres per month, and 65 fils for each cubic metre beyond that volume. Actual costs, as given by the Municipal Water Department, are about 110 fils per cubic metre from the Wadi Sir pumping station and 45 to 50 fils from the other stations.

Table 18

COST OF MOVING WATER FROM AZRAQ TO AMMAN (JORDANIAN DINARS)

M^3/hr	750	750	1,000
Pipe diameter, inches	20	24	24
HP required	2,660	1,350	2,350
Initial expenditures			
Equipment	26,400	14,150	23,300
Pipe	1,250,000	1,500,000	1,500,000
Annual expenses			
Pumping	147,000	74,500	140,000
Maintenance and salaries	27,000	26,400	27,600
20-year loan at 5% interest			
Principal	63,800	76,000	76,500
Average interest	31,900	38,000	38,250
Total annual cost	269,700	214,900	282,350
Cost per m^3 fils	40.8	32.5	32.2

Note: Power costs assumed as 9 fils per KWH.
Pumping rate assumed as 24 hours per day, 365 days per year.

211. In addition to Amman, a pipeline from Azraq could serve the city of Zarqa, which has recently experienced a very rapid growth and now has a population of 96,000. The oil refinery near by is also a relatively high consumer of water.

212. In a letter to the Central Water Authority on 17 March 1964, Mr. D. J. Burdon, the FAO regional technical officer (irrigation and water conservation), strongly urged the establishment of a national plan for water-resources development and conservation in Jordan. If and when such a plan is established, the utilization of Azraq water for a supplementary municipal supply to the Amman metropolitan area should be in accord with the plan.

VIII. CONCLUSIONS AND RECOMMENDATIONS

213. According to the estimates in this report, the safe perennial yield of ground water in the Azraq Basin is not adequate to meet the requirements of previously proposed plans for irrigation of large areas of additional land within the Basin, or for exportation of large quantities of water out of the Basin. Previous estimates of the percentage of precipitation that reaches the water-table and of the quantity of water that is discharged at El-Azraq are too high and cannot be used as a basis for planning additional development of the water resources of the Basin.

214. Under most of the Basin, the Kurnub formation is at too great a depth for economic development of ground-water supplies and indications are that it has a low permeability. The Ajlun formation does not contain significant quantities of ground water at the few places where it was penetrated by wells. The water-bearing properties of the Belqa formation range from poor to excellent; however, large-capacity wells can be developed in the upper zone of unconfined ground water in limited areas of high permeability. The water-production potential of the B 2 artesian aquifer was established only in well AZ-1, where it is very good, although the water is of poor quality for irrigation. If it is decided in the future to develop the aquifer for some other use, it could probably be developed without danger of upsetting the salt-water-fresh water balance in the shallow ground water at El-Azraq. However, development probably would cause a rapid regional decline in the piezometric head. The water would be obtained from expansion of the ground water upon release of pressure and from compaction of the aquifer; thus, the cost of pumping might become prohibitive before actual unwatering of the aquifer could begin. The volcanic rocks function chiefly as a recharge medium for the underlying sedimentary rocks and yield water to wells in only a few places; insufficient data are available to determine their regional water-bearing properties. Indications are that the Plateau group is not important as a water-bearing formation, and wells in the unconsolidated alluvial deposits generally have low yields, except along the axes of some wadies near El-Azraq.

215. The chemical quality of the ground water and the soils has an important bearing on the feasibility of additional agricultural development in the Basin. According to accepted methods of determining water utility, the quality of the ground water in most of the Basin is chemically unsuitable for irrigation of most of the soils. Only the ground water from the basalt shield area is suitable for either irrigation or domestic use. Most of the soils in and bordering Qá Azraq are too thin or too saline to be suitable for reclamation by irrigation. The soils that were found to be suitable would require irrigation water with a low salt content, extensive leaching, treatment with chemical amendments and good drainage.

216. Of the total amount of ground water discharged at El-Azraq, about 1,200 m^3/hr is perennially available for use. This represents the quantity that could theoretically be extracted year after year without mining ground water from storage. However, should this perennial supply be developed by withdrawals from wells in the basalt shield area, the flow of the springs at El-Azraq would be reduced and the local economy would suffer. There should be no additional pumping from wells near the springs or from the springs themselves because of the danger of salt-water encroachment. Any additional development of the unconfined ground water should be at a sufficient distance from the springs so that the base of the aquifer is at an elevation greater than the head of the salt-water at Qá Azraq and thus would be out of danger of contamination by salt-water intrusion.

217. Available field data indicate that, in addition to the ground water perennially available in the Azraq Basin, a large volume of water is contained in storage in the geologic formations. This ground water in storage represents a resource that may have great potential value to Jordan if properly managed. It seems unwise to mine this stored water for irrigation agriculture under current conditions because, as the quantity in storage was depleted, the ground water-table would decline and the costs of irrigation would steadily increase. Economic considerations eventually would prohibit further exploitation and the area would have to return to a desert economy. On the other hand, if it becomes necessary to develop the stored water for municipal or industrial supplies elsewhere in Jordan, there is reason to believe that relatively large quantities for such purposes could be pumped for a long period of time. Should the Jordanian Government decide to mine ground water from storage for exportation from the Azraq Basin, the aquifers must be further explored and evaluated so that they may be exploited in the best national interest.

218. Any large-scale development of the perennially available ground water will cause the springs at El-Azraq eventually to stop flowing. In such an event, even the current limited irrigation agriculture could not be supported and the economy of El-Azraq probably should be relegated to the production of salt. Plans should also be made to relocate that part of the population of El-Azraq that has been dependent on agriculture.

219. During current and future pumping and exportation of water from the Druze North Springs, either measurements of electrical conductivity or determination of chlorides should be done on the spring water regularly to be sure the chemical quality is not deteriorating. The weir installations at the springs should be maintained and daily readings of discharge should be continued.

220. In the future, the Government of Jordan and its Central Water Authority should require all consultants and contractors employed by them for water-resources investigations to submit all original data and measurements, in order that interpretations may be checked and evaluated. All drilling should be carefully supervised and restricted to areas approved by the Central Water Authority. During drilling and testing operations, the following should be required: detailed sampling and recording of data, complete development of wells, controlled aquifer and well-performance tests, and careful analysis and evaluation of the resulting data.

221. Basic data on water-resources studies should be recorded on standardized forms and kept on file in Amman. The Keysort card system is convenient because one card can contain the important basic data on a well, such as the geological log, construction details, water-level measurements, chemical analysis of the water, results of pumping tests, etc. The system also is useful for recording inventories of springs or discharge measurements of streams. The cards permit rapid sorting and location of data, and photostatic copies can be made for use in the field. With such a data-filing system, hydrogeological data in Jordan could be integrated and thus be more efficiently utilized for future studies.

ANNEX I

RECORDS AND LOGS OF SELECTED WELLS AND TEST HOLES IN THE AZRAQ BASIN

(TABLES 19 and 20)

Table 19

RECORDS OF SELECTED WELLS AND TEST HOLES IN THE AZRAQ BASIN

Well	Map co-ordinates (Palestine grid) E N	Altitude of land surface (metres) [a]	Year completed	Depth of well (metres)	Diameter of well (inches)	Water Level: Above (+) or below land surface (metres)	Water Level: Date of measurements	Water-yielding Unit[b]	Specific capacity (gpm/ft)	Total dissolved solids (ppm)	Chloride (ppm)	Remarks
AZ- 1	321.200-142.160	514.97	1963	1,299	18-5	+6.97	Nov. 1964	B 2	5.5	1,180	300	[c] [d]Flows
AZ- 2	282.550-163.520	600	1962	163	17	70.76	Jan. 1964	B 2	1	—	—	
AZ- 3	296.400-136.700	598	1963	181	17	59.50	Jan. 1964	B 3	—	1,920	—	[c] [d]
AZ- 4	295.650-145.950	615	1963	202	17-12	69.20	Jan. 1964	B 3	—	1,960	—	[c]
AZ- 5	342.225-144.670	575.95	1963	131	16	60.50	Jan. 1964	B 3	—	1,930	750	[c]
AZ- 8	320.960-141.950	515.29	1963	94	10	7.80	Mar. 1964	B 4	10	380	105	[c]
AZ- 9	322.650-140.550	509.37	1963	69	14	1.60	1963	Qal	—	1,550	685	Salinity-test well
AZ-10	336.780-139.950	520.33	1963	116	17-10	4.95	Jan. 1964	(?)	—	1,010	217	[c]
AZ-11	320.300-141.340	520.77	1963	88	14-10	13.50	Mar. 1964	B 4	700	—	—	
AZ-12	322.340-149.320	521.55	1963	255	18-12	4.45	Mar. 1964	V B	180	310	—	[c]
AZ-13	323.800-141.350	506.30	1963	55	14	+1.58	Apr. 1963	(?)	—	4,000	2,010	[c]Flowed 1963
AZ-14	329.610-127.360	511.57	1963	300	15-12	4.93	Jan. 1964	(?)	—	42,000	23,200	[c]
AZ-15	320.400-120.920	526.20	1963	54	14-13	22.40	Jan. 1964	B A	3	2,500	805	[c]
AZ-19	341.500-107.700	548	1963	301	16-9	21	1963	B 5	1	1,510	—	[c]Desert watering point
AZ-21	325.030-114.450	563.48	1963	90	16-13	39.20	Jan. 1964	B	—	1,760	585	[c]
AZ-22	306.170-119.660	578.05	1963	79	17	49.80	1963	B	—	1,500	392	[c]
AZ-23	293.200-125.250	624	1963	124	16-12	81.60	Mar. 1964	B 3	10	600	92	[c]
AZ-29	297.350-104.750	690	1963	162	17-12	—	—	—	—	—	—	Dry
P- 1	331.000-136.200	509.75	1963	6	4	3.80	Jan. 1963	B	—	—	—	
P- 3	337.260-138.740	520.67	1963	11	4	7.30	—	—	—	—	—	
P- 4	325.225-146.700	511.92	1963	4	4	2.25	Jan. 1963	V	—	—	—	
P- 5	326.700-128.070	507.16	1963	6	4	2.10	Feb. 1963	(?)	—	—	—	
P- 6	331.370-125.950	510.24	1963	8	4	2.95	Jan. 1963	(?)	—	—	—	
P-11	322.200-138.220	507	1963	8	4	1.19	Feb. 1963	(?)	—	—	—	
PA-1A	322.030-137.940	508.41	1956	152	18-10	0.76	1956	(?)	—	—	—	
PA-2	321.760-138.500	516.69	1956	46	18-16	9.05	1956	B	—	—	—	
PA-3	315.670-143.200	556.56	1956	73	18	48.70	Dec. 1962	B 4	—	440	—	[c]
PA-4	316.575-144.275	554.86	1957	247	16-10	36.00	Feb. 1964	B 3	2	980	—	[c]
PA-5	313.460-141.150	555.16	1957	307	16-8	46.00	Dec. 1962	B 4	—	—	—	[d]Log not available
PA-6	320.410-139.750	531.52	1957	31	16	25	1957	(?)	—	435	—	[c]
PAB- 7B	314.883-131.435	524.50	1958	404	16-8	3	1958	B	—	—	—	
PAB- 8	313.960-131.570	526.75	1958	130	16-12	2.50	1958	B	4	—	—	
PAB- 9	311.952-130.470	531.26	1958	395	18-10	9	1958	B	—	—	—	
PAB-10	309.950-128.970	540.95	1958	77	16	13	1958	B	—	—	—	
PAB-11	311.900-128.620	536.87	1958	115	18	11.60	July 1963	B	—	—	—	Hydrograph (fig. IV)
PAB-12	312.200-135.400	527.44	1958	362	15-10	6.60	1958	Qal	1	1,256	—	
PAB-13	308.987-136.949	539.65	1958	178	18-12	30.00	May 1958	B	—	—	—	
PAB-14	306.058-129.312	550.81	1958	98	16	22.25	1958	B 4	—	—	—	
PAB-15	302.060-133.050	557.77	1958	335	16	29	1958	B 4	2	—	—	
PAB-17	307.168-132.592	538	1958	280	16-10	13.85	May 1962	B 4	—	840	—	
S-12	313.850-148.100	536.76	1956	200	18-10	21.20	Jan. 1964	B	—	—	—	Hydrograph (fig. IV)

Table 19

RECORDS OF SELECTED WELLS AND TEST HOLES IN THE AZRAQ BASIN *(Continued)*

Well	Map co-ordinates (Palestine grid) E N	Altitude of land surface (metres) [a]	Year completed	Depth of well (metres)	Diameter of well (inches)	Water Level: Above (+) or below land surface (metres)	Water Level: Date of measurements	Water-yielding Unit[b]	Specific capacity (gpm/ft)	Total dissolved solids (ppm)	Chloride (ppm)	Remarks
Hammam No. 2	279.325-165.865	600	—	140	16	72.20	Feb. 1964	B	5	215	400	[c]Domestic and stock well
Hababiya No. 1	298.050-162.230	584.42	1958	66	—	60	1958	V	—	—	—	
Hababiya No. 3	296.975-164.950	587.72	1957	106	16-10	64.30	1957	V	—	200	—	[c]Domestic and stock well
Shomari No. 1												
AG-1(101)	316.320-130.050	523.49	1954(?)	38	10	9.55	Feb. 1964(?)	Qal	30	1,510	—	[c]Irrigation well
AG-3(105D)	321.000-129.000	514.67	1954	46	6	4.57	Nov. 1954	B 4	5	—	—	
103-B	317.500-126.160	525.73	1954	66	—	10.60	1954(?)	B 4	1	—	—	
104-C	320.150-129.720	514.27	1954(?)	46	—	4.87	1954(?)	B 4	—	5,000	—	
H-5 No. 1	351.600-118.200	715	—	273	6	191	—	(?)	—	—	—	Domestic well
Umari No. 2	341.000-118.000	520	—	52	—	9	—	(?)	—	2,843	—	
Umari No. 3	341.750-117.320	520	—	124	18-14	6	—	(?)	—	3,000	—	Well filled in
Tapline 6-A	336.000-169.500	805.81	1950	229	12-7	211	1950(?)	V	—	525	—	[c]Domestic well
Safra No. 1	279.990-137.389	748	1958	2,582	20-10	366	1958	(?)	—	—	—	Oil-test hole
I-27	325.606-145.150	517	—	15	—	9.1	— (?)	(?)	—	—	—	
I-29	324.750-145.050	520	—	31	—	1.8	—	Qal	—	—	—	
I-35	326.100-144.150	510	—	25	—	18.3	—	(?)	—	—	1,650	
I-41	317.400-135.800	507	1949	31	—	2.1	1949(?)	Qal	—	—	257	

[a] Altitudes followed by decimals are based on spirit-levels; others are interpolated from topographical maps.
[b] Water-yielding unit: B, Belqa Series and number of unit where known; V, volcanics; Qal, alluvium.
[c] For chemical analysis of the water, see table 6.
[d] For electric and gamma-ray logs, see figure XV in pocket.

Table 20

LOGS OF SELECTED WELLS AND TEST HOLES IN THE AZRAQ BASIN

AZ-1 (321.200—142.160)

Drilled by the United Nations Special Fund and the Central Water Authority with both a cable-tool and a standard rotary drilling rig. Free artesian flow from Belqa 2 aquifer estimated at 190 gpm with an artesian head measured at 22.8 feet above land surface in November 1964. For additional data on this well, see chapter VI and figure XV in pocket.

Lithology	*Thickness (metres)*	*Depth (metres)*
Quaternary deposits		
Soil, red, gypsiferous, with flint particles	8	8
Belqa 4		
Chert, brown, interbedded with soft, white chalk and chalky limestone; contains water between 10 and 55 metres	48	56
Belqa 3		
Marl, gray, soft, with traces of pyrite	74	130
Marl, gray, soft, bituminous, with traces of chert	54	184
Shale, gray, phosphatic, with traces of chert and light-blue marl	51	235
Shale, very hard, phosphatic, with layers of black and dark-gray chert	21	256
Limestone, gray-white, fossiliferous, interbedded with gray-blue shale and marl, with traces of glauconite. Contains saline water between 235 and 322 metres	155	411
Belqa 2		
Limestone, white to gray, interbedded with friable, quartzose sandstone and gray to black chert, some thin layers of calcareous sandstone and gray marl. Contains water under artesian pressure between 421 and 587 metres, which will flow at land surface when head valve is opened	191	602
Belqa 1		
Marl and shale	17	619
Ajlun 7		
Limestone, white, amorphous, hard, interbedded with layers of sandstone, shale, and chert. Contains thin layers of marl and becomes fossiliferous between 705 and 746 metres	127	746
Ajlun 5-6		
Marl, blue-gray, shaly, interbedded with light-gray limestone and shale	84	830
Ajlun 4		
Limestone, gray, with some shale	76	906
Ajlun 3		
Shale, light to dark gray, with layers of clay and black limestone and some pyrite	83	989
Ailun 1-2		
Limestone, light gray, platy, interbedded with shale and clay	75	1,064
Shale, dark gray, interbedded with layers of limestone and clay; contains pyrite and micro-fossils	191	1,255
Kurnub sandstone		
Sandstone, fine-grained, friable; with thin layers of shale and sandy marl at top; contains water under artesian pressure that rose to 90 metres below land surface after initial swabbing test	44	1,299

AZ-2 (282.550—163.520)

Drilled by the United Nations Special Fund and the Central Water Authority with a cable-tool drilling rig. Uncased hole. Bailed at 30 gpm with drawdown of 29 feet after 2 hours of bailing.

Lithology	*Thickness (metres)*	*Depth (metres)*
Quaternary deposits		
Soil, clay, and gravel	8	8
Belqa 2		
Chalk, white, with limestone and chert. Struck water under artesian pressure at 76 metres that rose to 71 metres below land surface	124	132
Belqa 1		
Marl, chalky	15	147
Ajlun 7		
Limestone	5	152
Log missing	11	163

AZ-3 (296.400—136.700)

Drilled by the United Nations Special Fund and Central Water Authority with a cable-tool drilling rig. Eighteen metres of 12-inch casing at top; rest of hole encased. For electric and gamma-ray logs, see figure XV.

Lithology	*Thickness (metres)*	*Depth (metres)*
Belqa 4		
Chalk, white, soft, with chalky marl and multi-coloured chert	43	43
Belqa 3		
Marl, gray, interbedded with layers of black chert; bituminous between 55 and 58 metres	73	116
Marl, gray, sandy, bituminous, with traces of disseminated pyrite	41	157
Marl, phosphatic between 157 and 166 metres, and between 170 and 178 metres	24	181

AZ-4 (295.650—145.950)

Drilled by the United Nations Special Fund and the Central Water Authority with a cable-tool drilling rig. Six metres of 13⅜-inch casing at top; rest of hole encased.

Lithology	*Thickness (metres)*	*Depth (metres)*
Quaternary deposits		
Sand and chert gravel	20	20
Belqa 4 (?)		
Chert	20	40
Belqa 3		
Marl, sandy, with sandy shale and chert	30	70
Log missing; struck water at 70 metres	5	75
Chalk and chalky marl, with bituminous marl at bottom	127	202

AZ-5 (342.225—144.670)

Drilled by the United Nations Special Fund and the Central Water Authority with a cable-tool drilling rig. Uncased hole.

Lithology	*Thickness (metres)*	*Depth (metres)*
Quaternary deposits		
Soil, brown and chert gravel	7	7

Lithology	Thickness (metres)	Depth (metres)
Belqa 4		
Chalk, red, marly, with some limestone at top and friable sand at bottom	45	52
Belqa 3		
Limestone, rose to white, with chalky, red marl	26	78
Marl, gray-blue, bituminous, with layers of black chert and traces of disseminated pyrite	53	131

AZ-8 (320.960—141.950)

Drilled by the United Nations Special Fund and the Central Water Authority with a cable-tool drilling rig. Uncased hole. Test-pumped in March 1964 at 473 gpm for 24 hours with maximum drawdown of 47 feet.

Quaternary deposits		
Alluvium with chert gravel	10	10
Belqa 4		
Chert, brown, thick-bedded, with thin layers of white chalk	38	48
Belqa 3		
Marl, gray, bituminous, interbedded with thin layers of black chert	46	94

AZ-9 (322.650—140.550)

Drilled by the United Nations Special Fund and the Central Water Authority with a cable-tool drilling rig. Twenty metres of 13⅜-inch casing at top; rest of hole uncased. Bailed at 85 gpm; drawdown not recorded.

Quaternary deposits		
Soil yellow-brown and light-green bentonitic clay	18	18
Gravel, composed of particles of limestone and brown chert	12	30
Belqa 4		
Chalk, white, soft, interbedded with brown chert	37	67
Belqa 3		
Marl, gray, bituminous	2	69

AZ-10 (336.780—139.950)

Drilled by the United Nations Special Fund and the Central Water Authority with a cable-tool drilling rig. Cased with 9⅝-inch casing from land surface to 54 metres; hole backfilled to 54 metres. No record of perforations.

uaternary deposits		
Alluvium	8	8
Log between 8 and 85 metres unclear		
Limestone, white, amorphous, interbedded with sand and gravel (?) and sandy clay (?)	43	51
Sand and gravel (?), chalky marl, and sandstone, interbedded	34	85
Belqa 5		
Marl, chalky	31	116

Lithology	Thickness (metres)	Depth (metres)

AZ-11 (320.300—141.340)

Drilled by the United Nations Special Fund and the Central Water Authority with a cable-tool drilling rig. Twenty metres of 13⅜-inch casing at top; rest of hole encased. Test-pumped at 700 gpm for 24 hours in March 1964 with maximum drawdown of 1 foot. (?)

Recent deposits		
Soil, brown, with flint particles	2	2
Belqa 4		
Chalk, white, soft, with layers of white limestone and brown, concretionary chert; contains abundant water at 14 metres	61	63
Belqa 3		
Marl, gray, bituminous and black, bituminous limestone with some chert	25	88

AZ-12 (332.340—149.320)

Drilled by the United Nations Special Fund and the Central Water Authority with a cable-tool drilling rig. Uncased hole. Test-pumped in March 1964 at 750 gpm for 24 hours with maximum drawdown of 4.2 feet (?).

Volcanics		
Basalt, with some intercalated layers of clay	57	57
Belqa 4 (?)		
Chalk and marl, with beds of clay	57	114
Belqa 3 (?)		
Chalk and marl, with numerous chert concretions and some limestone	85	199
Marl, bituminous, with black chert, becomes phosphatic below 250 metres	56	255

AZ-13 (323.800—141.350)

Drilled by the United Nations Special Fund and the Central Water Authority with a cable-tool drilling rig. Cased with 13⅜-inch casing from surface to 45 metres; rest of hole uncased. Reportedly started flowing at rate of 250 gpm during bailing test at completion of drilling.

Recent deposits		
Top soil and alluvium	7	7
Volcanics		
Ash, volcanic, with some intercalated layers of clay	42	49
Belqa 4		
Chert and limestone	6	55

AZ-14 (329.610—127.360)

Drilled by the United Nations Special Fund and the Central Water Authority with a cable-tool drilling rig. Twenty metres of 13⅜-inch casing at top; rest of hole uncased.

Recent deposits		
Alluvium	3	3
Belqa 5 (?)		
Marl	11	14

Lithology	*Thickness (metres)*	*Depth (metres)*
Belqa 4 (?)		
Limestone, thin-bedded, sandstone (?), marl, and clay between 30 and 33 metres	19	33
Belqa 3 (?)		
Marl, chalky, with micro-fossils; contains chert between 285 and 300 metres	267	300

AZ-15 (320.400—120.920)

Drilled by the United Nations Special Fund and A. H. Arekat, drilling contractor, with a cable-tool drilling rig. Uncased hole. Bailed at 50 gpm with drawdown of 16.5 feet after 1½ hours of bailing.

Quaternary deposits		
Soil, red-brown, and detrital flint pebbles	10	10
Belqa 4		
Chalk, white, soft, with some brown chert. Struck water at 23 metres	35	45
Belqa 3		
Marl, gray, soft, chalky, with traces of pyrite	9	54

AZ-19 (341.500—107.700)

Drilled by the United Nations Special Fund and A. H. Arekat, drilling contractor, with a cable-tool drilling rig. Casing record unclear. Bailed at approximately 40 gpm with an approximate drawdown of 50 feet after ⅓ hour of bailing.

Quaternary deposits		
Soil, brown, calcareous with particles of detrital chert at bottom	10	10
Belqa 5 (?)		
Sand (?) with limestone	5	15
Marl, light brown, chalky with some chert	32	47
Belqa 4 (?)		
Clay, red, marly	23	70
Belqa 3 (?)		
Marl, gray, chalky, with interbedded layers of chalk; contains some chert, limestone (?), and disseminated pyrite	231	301

AZ-21 (325.030—114.450)

Drilled by the United Nations Special Fund and A. H. Arekat, drilling contractor, with a cable-tool drilling rig. Cased for 15 metres at top; rest of hole uncased.

Recent deposits		
Soil and detrital gravel	15	15
Belqa 4		
Chalk	45	60
Belqa 3 (?)		
Marl, chalky	30	90

Lithology	*Thickness (metres)*	*Depth (metres)*

AZ-22 (306.170—119.660)

Drilled by the United Nations Special Fund and the Central Water Authority with a cable-tool drilling rig. Uncased hole. Bailed dry after ½ hour bailing at 30 gpm.

Recent deposits		
Soil, brown, with gravel	4	4
Belqa 4		
Chalk, white, soft, with some brown chert; struck water at 50 metres	46	50
Belqa 3		
Chert, black	4	54
Marl, gray, soft, with some chert; becomes bituminous at bottom	25	79

AZ-23 (293.200—125.250)

Drilled by the United Nations Special Fund and the Central Water Authority with a cable-tool drilling rig. Uncased hole, but may be cased for use as desert watering point. Bailed at 40 gpm with drawdown of about 4 feet after 2 hours of bailing.

Recent deposits		
Soil, red, calcareous, with chert gravel	5	5
Belqa 4		
Chalk, white to yellow, soft, with interbedded dark brown chert and particles of limestone	35	40
Chalk, white, soft, interbedded with layers of chalky limestone and brown chert	44	84
Belqa 3		
Marl, gray, chalky, interbedded with layers of buff to white limestone and brown to black chert; becomes bituminous below 120 metres. Struck water under artesian pressure at 89 metres that rose to 82 metres below land surface	40	124

AZ-29 (297.350—104.750)

Drilled by the United Nations Special Fund and the Central Water Authority with a cable-tool drilling rig. Uncased hole. Dry.

Recent deposits		
Soil, brown, with detrital chert and limestone particles	3	3
Belqa 4		
Chalk, white, interbedded with semi-crystalline to amorphous limestone and brown chert	143	143
Belqa 3		
Marl, soft, bituminous, with black chert	19	162

P-1 (331.000—136.200)

Drilled by the United Nations Special Fund and the Central Water Authority with a Portadrill air-rotary drilling rig. Cased to bottom with 2-inch pipe.

Recent deposits		
Clay, brown, chert, gravel, with some fine sand	2	2
Belqa 5 (?)		
Chalk and flint	4	6

P-3 (337.260—138.740)

Drilled by the United Nations Special Fund and the Central Water Authority with a Portadrill air-rotary drilling rig. Cased to bottom with 2-inch pipe.

Lithology	Thickness (metres)	Depth (metres)
Recent deposits		
Soil, gray, with chert and gypsum	2	2
Belqa 5		
Chalk, white, soft, with green clay between 8 and 9.3 metres	9	11

P-4 (325.225—146.700)

Drilled by the United Nations Special Fund and the Central Water Authority with a Portadrill air-rotary drilling rig. Cased to bottom with 2-inch pipe.

Lithology	Thickness (metres)	Depth (metres)
Recent deposits		
Clay, green, and fine sand	3	3
Volcanics		
Basalt, contains water	1	4

P-5 (326.700—128.070)

Drilled by the United Nations Special Fund and the Central Water Authority with a Portadrill air-rotary drilling rig. Cased to bottom with 2-inch pipe.

Lithology	Thickness (metres)	Depth (metres)
Recent deposits		
Soil, red-brown, with fine sand and abundant gypsum	2	2
Belqa 5		
Chalk, white, with green marl	4	6

P-6 (331.370—125.950)

Drilled by the United Nations Special Fund and the Central Water Authority with a Portadrill air-rotary drilling rig. Cased to the bottom with 2-inch pipe.

Lithology	Thickness (metres)	Depth (metres)
Recent deposits		
Soil, red-brown, with chert, underlain by red-brown sand	3	3
Belqa 5		
Marl, yellow-green and white chalk. Reportedly struck water at 7.5 metres	5	8

P-11 (322.200—138.220)

Drilled by the United Nations Special Fund and the Central Water Authority with a Portadrill air-rotary drilling rig. Cased to the bottom with 2-inch pipe.

Lithology	Thickness (metres)	Depth (metres)
Recent deposits		
Clay, red, soft, with flint and chert gravel	4	4
Belqa 4		
Chalk, white, with interbedded chert	4	8

PA-1A (322.030—137.940)

Drilled by Baker-Harza with a cable-tool drilling rig. Casing record unclear.

Lithology	Thickness (metres)	Depth (metres)
Recent deposits		
Soil and gravel	5	5
Belqa 4		
Chert, chalky limestone, and chalk	63	68
Belqa 3		
Marl, gray, soft bituminous	49	117
Shale, blue, phosphatic	35	152

PA-2 (322.030—137.940)

Drilled by Baker-Harza with a cable-tool drilling rig. Casing record unclear.

Lithology	Thickness (metres)	Depth (metres)
Belqa 4		
Limestone, chalky, with brown chert	37	37
Belqa 3		
Marl, gray, chalky, with bituminous, gray shale	9	46

PA-3 (315.670—143.200)

Drilled by Baker-Harza with a cable-tool drilling rig. Uncased hole. Reportedly yielded 220 gpm during pump test made at completion of drilling.

Lithology	Thickness (metres)	Depth (metres)
Recent deposits		
Detrital gravel	2	2
Belqa 4		
Chalk, white, interbedded with brown chert and some limestone; struck water at 54 metres	53	55
Belqa 3 (?)		
Limestone, white, amorphous, with some black chert	18	73

PA-4 (316.575—144.275)

Drilled by Baker-Harza with a cable-tool drilling rig. Cased with 10-inch casing to 37 metres below land surface. Test-pumped in February 1964 at 142 gpm for 24 hours with a maximum drawdown of 71 feet.

Lithology	Thickness (metres)	Depth (metres)
Recent deposits		
Top soil	1	1
Belqa 4		
Limestone and chert	44	45
Belqa 3		
Marl, with interbedded chert and phosphatic shale. Struck water at 55 metres	202	247

PA-5 (313.460—141.150)

Drilled by Baker-Harza with a cable-tool drilling rig. Casing record unclear. For electric and gamma-ray logs, see figure XV.

Lithology	Thickness (metres)	Depth (metres)
Belqa 4		
Chalk, white, soft, interbedded with brown chert	52	52
Belqa 3		
Marl, gray, with interbedded black chert and gray shale. Log missing between 95 and 98 metres...	73	125
Marl, gray, bituminous........................	8	133
Marl, with some black chert..................	82	215
Shale, sandy, phosphatic between 215 and 249 metres. Log missing between 222 and 236 metres.		
Marl, blue-gray, interbedded with sand (?), limestone (?), and some black chert..............	92	307

PAB-7B (314.883—131.435)

Drilled by Baker-Harza with a cable-tool drilling rig. Casing record unclear. Reportedly yielded 70 gpm during pump test at completion of drilling.

Lithology	Thickness (metres)	Depth (metres)
Recent deposits		
Gravel......................................	1	1
Belqa 4		
Chalk, interbedded with chert and chalky marl..	31	32
Belqa 3		
Marl, gray, chalky, interbedded with layers of chalk and black chert.......................	218	250
Marl, bituminous, with layer of phosphatic marl between 348 and 350 metres..................	150	400
Belqa 2		
Chert......................................	4	404

PAB-8 (313.960—131.570)

Drilled by Baker-Harza with a cable-tool drilling rig. Cased to bottom with 12-inch casing, lower part of which is perforated. Gravel packed. Reportedly yielded 895 gpm with a drawdown of 218 feet during pump test made at completion of drilling.

Lithology	Thickness (metres)	Depth (metres)
Recent deposits		
Top soil underlain by gravel..................	5	5
Belqa 4		
Chalk, white and hard, white limestone, with traces of chert............................	14	19
Log missing between 19 and 86 metres..........	67	86
Belqa 3		
Marl, gray, chalky, interbedded with chert......	44	130

PAB-9 (311.952—130.470)

Drilled by Baker-Harza with a cable-tool drilling rig. Casing record unclear.

Lithology	Thickness (metres)	Depth (metres)
Recent deposits		
Top soil underlain by gravel..................	10	10
Belqa 4 (?)		
Limestone, white to gray, interbedded with chert and marl................................	51	61
Belqa 3		
Marl, chalky, with layers of chert and limestone..	178	239
Marl, gray, with thin layers of chert...........	149	388
Belqa 2		
Chert, black................................	7	395

PAB-10 (309.950—128.970)

Drilled by Baker-Harza with a cable-tool drilling rig. Cased from land surface to depth of 65 metres with 16-inch casing. Reportedly bailed at 44 gpm with a drawdown of 52 feet at completion of drilling.

Lithology	Thickness (metres)	Depth (metres)
Quaternary deposits		
Top soil underlain by gravel comprised of chert and limestone..............................	23	23
Belqa 4		
Chalk, white, soft, with layers of marl..........	35	58
Belqa 3		
Chert, black, interbedded with thin layers of gray, chalky marl...............................	19	77

PAB-11 (311.900—128.620)

Drilled by Baker-Harza with a cable-tool drilling rig. Cased from land surface to depth of 76 metres with 16-inch casing.

Lithology	Thickness (metres)	Depth (metres)
Recent deposits		
Detrital particles of chert and limestone.........	7	7
Belqa 4		
Limestone, interbedded with chert and marl.....	41	48
Belqa 3		
Marl interbedded with chert..................	67	115

PAB-12 (312.200—135.400)

Drilled by Baker-Harza with a cable-tool drilling rig. Casing record unclear. Reportedly bailed at approximately 65 gpm with an approximate drawdown of 70 feet after 1 hour of bailing.

Lithology	Thickness (metres)	Depth (metres)
Quaternary deposits		
Top soil underlain by gravel composed of limestone and chert. Struck water at 7 metres...........	16	16
Belqa 4		
Chalk, with thin layers of limestone............	24	40
Belqa 3		
Marl, chalky, interbedded with chalk...........	159	199
Chert, black, interbedded with gray, chalky marl.	145	344
Marl, gray, bituminous with traces of chert......	18	362

PAB-13 (308.987—136.949)

Drilled by Baker-Harza with cable-tool drilling rig. Cased to bottom with 12-inch casing; no record of perforations.

Lithology	Thickness (metres)	Depth (metres)
Recent deposits		
Gravel, composed of chert.....................	3	3
Belqa 4		
Chalk, white, soft to medium hard, with some chert......................................	55	58
Belqa 3		
Marl, gray, soft, contains black chert between 127 and 178 metres..............................	120	178

PAB-14 (306.058—129.312)

Drilled by Baker-Harza with a cable-tool drilling rig. Seven metres of 16-inch casing at top.

Lithology	Thickness (metres)	Depth (metres)
Recent deposits		
Sand and gravel (?)	5	5
Belqa 4		
Chalk with chert with some limestone	63	68
Belqa 3		
Marl, gray, with chert	30	98

PAB-15 (302.060—133.050)

Drilled by Baker-Harza with a cable-tool drilling rig. Only 3.5 metres of 16-inch casing at top; rest of hole uncased. Reportedly bailed at 44 gpm with a drawdown of approximately 23 feet at completion of drilling.

Lithology	Thickness (metres)	Depth (metres)
Recent deposits		
Soil underlain by gravel	5	5
Belqa 4		
Chalk, chalky limestone, and chert. Struck water between 37 and 41 metres	56	61
Belqa 3		
Marl, gray, soft, with layers of black chert; marl becomes hard and bituminous between 138 and 296 metres	235	296
Chert, black, with thin layers of gray marl	39	335

PAB-17 (307.168—132.592)

Drilled by Baker-Harza with a cable-tool drilling rig. Uncased hole.

Lithology	Thickness (metres)	Depth (metres)
Recent deposits		
Soil	1	1
Belqa 4		
Chalk with layers of chert. Contains water at 13.5 metres	59	60
Belqa 3		
Marl, gray, bituminous, with layers of chert	181	241
Shale, phosphatic, interbedded with black chert	39	280

S-12 (313.850—148.100)

Drilled by Baker-Harza with a cable-tool drilling rig. Cased from land surface to a depth of 194 metres with 10-inch casing. No record of perforations.

Lithology	Thickness (metres)	Depth (metres)
Recent deposits		
Gravel	2	2
Belqa 4		
Chalk, white, interbedded with brown chert	61	63
Belqa 3		
Marl, gray, with layers of black chert and sandstone (?); becomes bituminous below 115 metres. Log missing between 124 and 129 metres and between 164 and 176 metres	137	200

Hammam No. 2 (279.325—165.865)

Drilled with a cable-tool drilling rig. Cased from land surface to depth of 25.6 metres with 16-inch casing. Test pumped in February 1964 at 45 gpm for 24 hours with a maximum drawdown of 9.5 feet.

Lithology	Thickness (metres)	Depth (metres)
Quaternary deposits		
Gravel, composed mostly of chert with some limestone particles	16	16
Belqa 4 (?)		
Chalk, white, with layers of limestone	5	21
(Hamman No. 2 continues on next page)		
Belqa 3 (?)		
Marl, gray to pink, interbedded with brown chert	12	33
Belqa 2 (?)		
Limestone, with some chalk and gray to brown chert. Struck water at 73 metres	98	131
Log missing between 131 and 140 metres	9	140

Hababiya No. 1 (298.050—162.230)

Drilled by Baker-Harza with a cable-tool drilling rig. Uncased hole.

Lithology	Thickness (metres)	Depth (metres)
Recent deposits		
Alluvium	4	4
Volcanics		
Basalt. Struck water at 64.5 metres	62	66

Hababiya No. 3 (296.275—164.950)

Drilled by Baker-Harza with a cable-tool drilling rig. Cased to bottom with 10-inch casing; no record of perforations.

Lithology	Thickness (metres)	Depth (metres)
Recent deposits		
Top soil	3	3
Volcanics		
Basalt, black	56	59
Clay	4	63
Basalt, with traces of clay and calcite. Struck water at 64.7 metres	43	106

Shomari No. 1 AG-1 (101) (316.320—130.050)

Drilled by the Water Resources Department with a cable-tool drilling rig. Cased with 10-inch perforated casing to bottom; zone of perforations not recorded. Test-pumped in February 1964 at 400 gpm for 13½ hours with a maximum drawdown of 13.65 feet.

Lithology	Thickness (metres)	Depth (metres)
Quaternary deposits (?)		
Top soil and clay	4	4
Marl, blue (?), and white chalk (?), interbedded with sand and gravel composed of flint	27	31
Gravel, fine to coarse, contains plentiful water	7	38

Lithology	Thickness (metres)	Depth (metres)

AG-3 (105-D) (321.000—129.000)

Drilled by the Water Resources Department with a cable-tool drilling rig. Casing record unclear. Reportedly test-pumped at approximately 155 gpm for 47 hours with a drawdown of approximately 30 feet.

Belqa 4		
Chert and chalk	16	16
Limestone and chalk. Struck water at 14 metres	13	29
Chert and chalk	11	40
Belqa 3 (?)		
Marl, gray-blue	6	46
(Bottom of well backfilled with rock for 3 metres)		

103-B (317.500—126.160)

Drilled by the Water Resources Department with a cable-tool drilling rig. Uncased hole. Reportedly test-pumped at approximately 130 gpm with a drawdown of approximately 120 feet.

Recent deposits		
Alluvium	2	2
Belqa 4		
Chalk, interbedded with gray to brown flint, glauconitic marl, and black chert	64	66

104-C (320.150—129.720)

Drilled by the Water Resources Department with a cable-tool drilling rig. Uncased hole.

Recent deposits		
Alluvium	2	2
Belqa 4		
Chalk, white to gray. Struck water at 13.7 metres.	44	46

H-5 No. 1 (351.600—181.200)

Drilled by the Water Resources Department with a cable-tool drilling rig. Cased with 6-inch casing to bottom; zone of perforations not recorded.

Volcanics		
Basalt; contains olivine in upper part, and red, oxidized zones in the middle and lower parts	191	191
Conglomerate (?)	13	204
Basalt	6	210
Belqa 4 (?)		
Limestone, white, with some layers of soft marl.	17	227
Limestone, white, partly silicified, with interbedded gray, brown, and black flint	46	273

Umari No. 2 (341.000—118.000)

Drilled by the Water Resources Department with a cable-tool drilling rig. Uncased hole.

Lithology	Thickness (metres)	Depth (metres)
Recent deposits		
Top soil underlain by gravel	4	4
Formation name unknown		
Sand (?) and sandy clay (?)	9	13
Clay, blue	28	41
Limestone with gypsum	7	48
Sandstone (?)	4	52

Umari No. 3 (341.750—117.320)

Drilled by the Water Resources Department with a cable-tool drilling rig. Well was filled with debris and abandoned owing to bad-quality water encountered.

Recent deposits		
Top soil underlain by gravel	6	6
Formation name unknown		
Sandstone (?) and sandy clay	8	14
Clay, red and blue	7	21
Chalk	52	73
Clay, blue	14	87
Shale, blue, with limestone	7	94
Limestone, chert, and marl	10	104
Chert, chalk, sand (?), and gravel (?)	20	124

Tapline 6-A (336.000—169.500)

Drilled by the Water Resources Department with a cable-tool drilling rig. Cased with 12-inch casing for 4.8 metres at top, and with 7-inch casing to a depth of 228.7 metres. No record of perforations.

Volcanics		
Basalt, hard, fissured	118	118
Basalt, medium-hard, weathered	14	132
Basalt, hard	73	205
Basalt, medium-hard, weathered	24	229

Safra No. 1 (279.990—137.389)

Drilled by the Edwin W. Pauley Oil Co. with a standard rotary drilling rig. Thirty metres of 20-inch casing at top; 13⅜-inch casing from land surface to depth of 257 metres; 9⅝-inch casing from land surface to depth of 935 metres. No record of perforations.

Recent deposits		
Soil	3	3
Belqa 4		
Chert, brown, interbedded with white chalk	21	24
Log missing	47	71
Chert, brown, interbedded with chalk and limestone	22	93
Belqa 3		
Marl, gray, bituminous	48	141
Log missing	194	335
Belqa 2		
Chert, thick-bedded, with layers of limestone	40	375
Belqa 1		
Marl, chalky, with sand	7	382

Lithology	Thickness (metres)	Depth (metres)
Ajlun 7		
Limestone, white, grades into white chalk at bottom	163	545
Ajlun 5 and 6		
Limestone, gray, interbedded with white chalk and chalky marl	117	662
Ajlun 4		
Limestone, white, cryptocrystalline	63	725
Ajlun 3		
Shale, dark-gray	17	742
Limestone, gray, hard, interbedded with gray shale and marl	20	762
Ajlun 1 and 2		
Marl, dark gray, interbedded with dark-gray shale	131	893
Kurnub sandstone		
Sandstone, light gray, glauconitic, with layers of gray limestone and shale. Struck water 915 metres	42+	935+
(Log used for Azraq ground-water study only to depth of 935 metres; total depth of this well was 2,582 metres.)		

I-27 (325.606—145.150)

Drilled by the Water Resources Department with a cable-tool drilling rig. Uncased hole.

Recent deposits		
Gravel	3	3
Volcanics		
Basalt	6	9
Formation name unknown		
Sand, with clay near bottom	6	15

Lithology	Thickness (metres)	Depth (metres)

I-29 (324.750—145.050)

Drilled by the Water Resources Department with a cable-tool drilling rig. Uncased hole.

Recent deposits		
Gravel and silt. Struck water at 1.8 metres	6	6
Volcanics		
Basalt	6	12
Formation name unknown		
Clay	6	18
Limestone, marl, and sand	13	31

I-35 (326.100—144.150)

Drilled by the Water Resources Department with a cable-tool drilling rig. Uncased hole.

Recent deposits		
Soil	4	4
Clay, sand, and gravel	15	19
Volcanics		
Basalt	6	25

I-41 (317.400—135.800)

Drilled by the Water Resources Department. Uncased hole.

Quaternary deposits (?)		
Gravel. Struck water at 3.3. metres	12	12
Clay	2	14
Gravel	12	26
Clay	1	27
Gravel	4	31

ANNEX II

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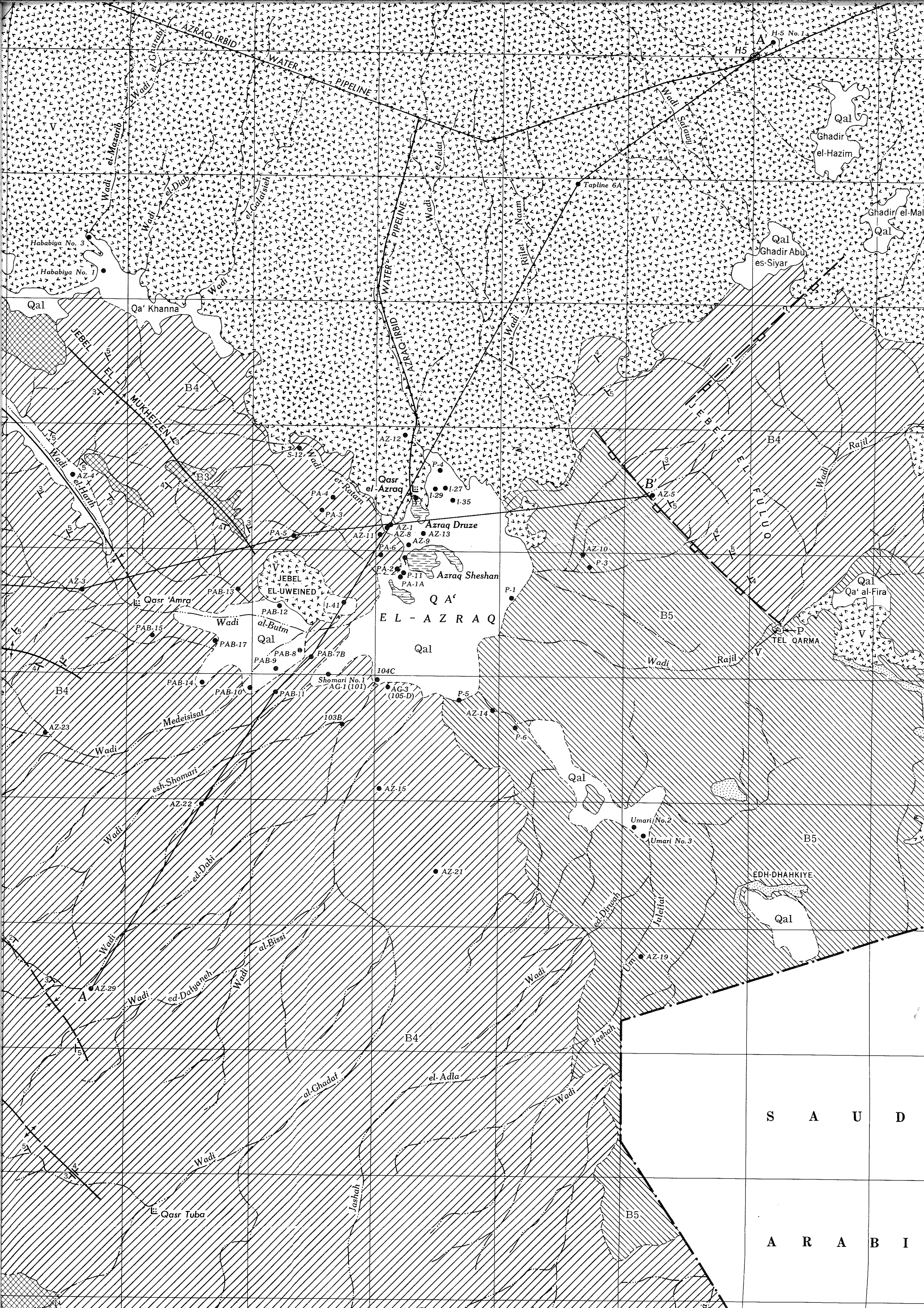
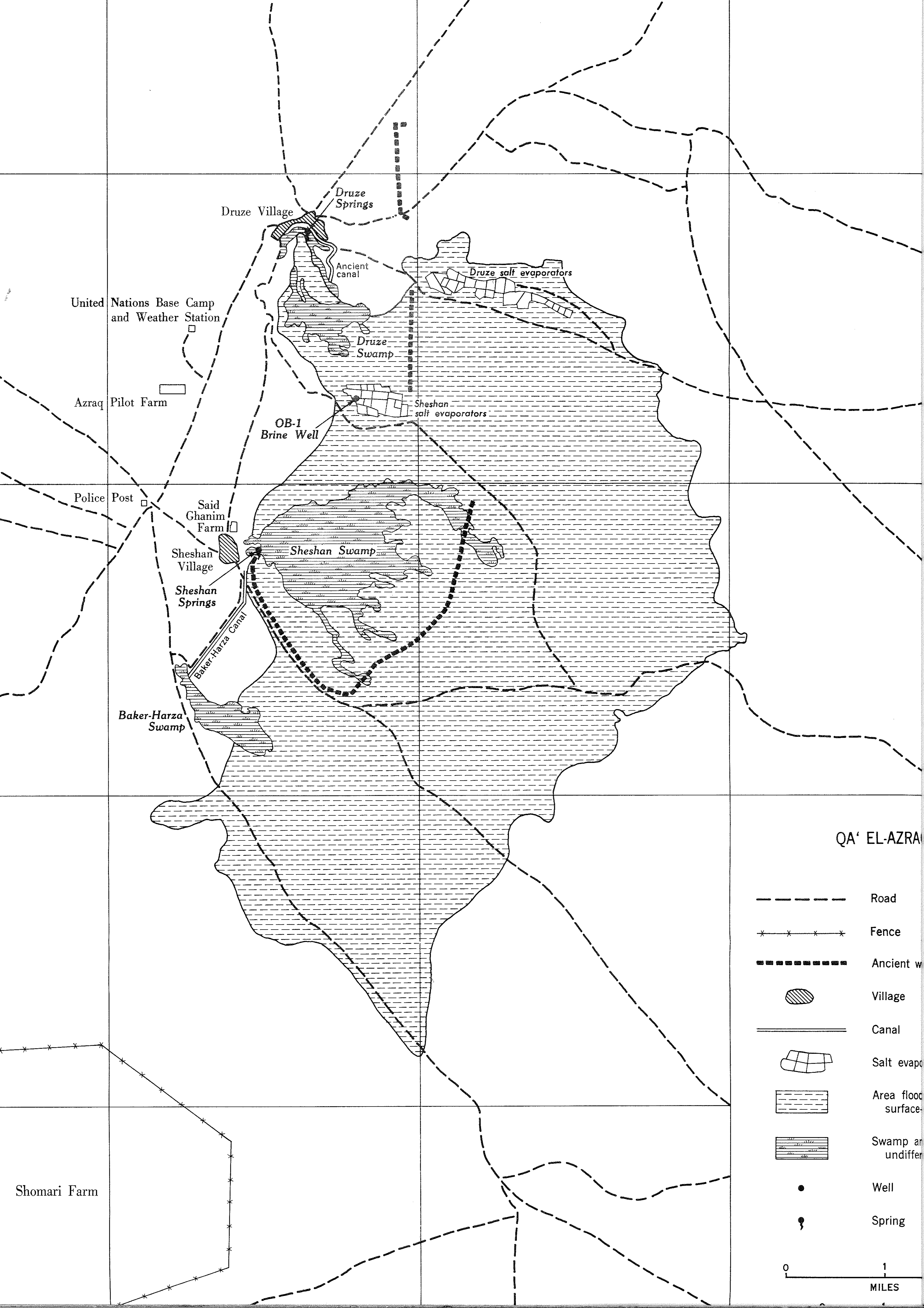
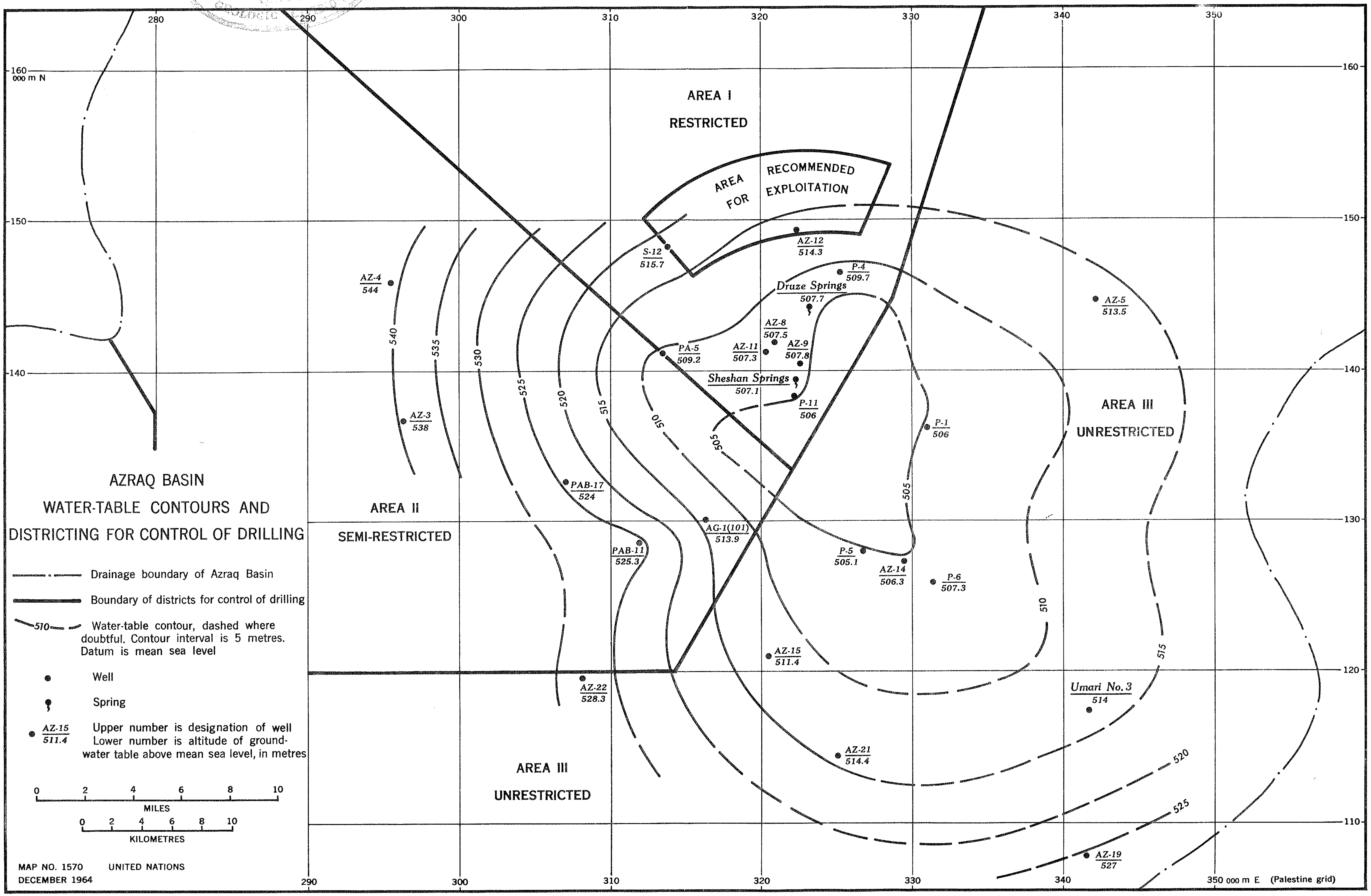


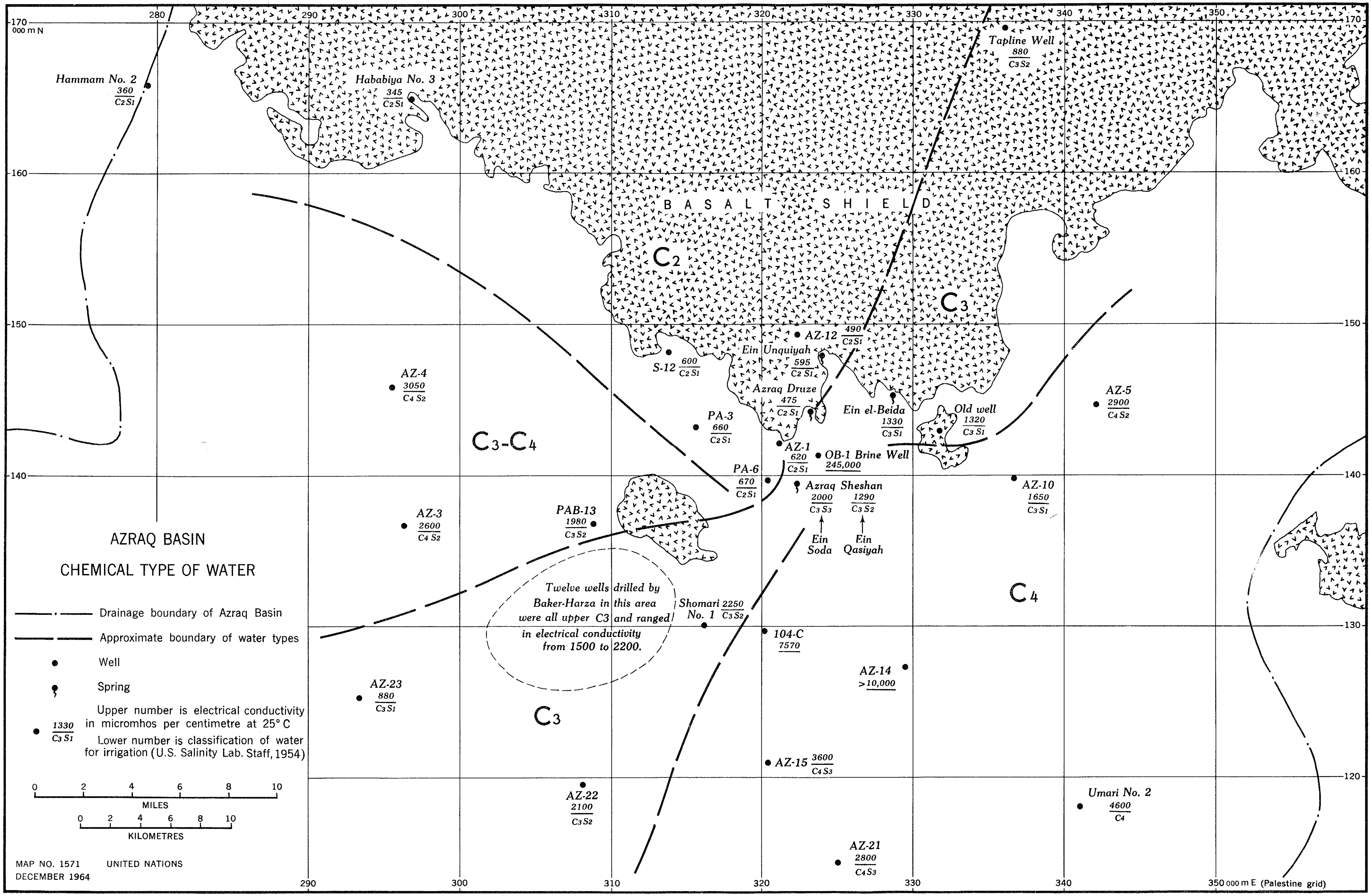
AZRAQ-IRBID WATER PIPELINE
Wadi el-Ghurab
Wadi el-Mazarib
Wadi el-Diab
Wadi el-Qalaisieh
Wadi el-Jelat
Wadi Salauy
Rillet Naam
Wadi
H5
H-5 No.1
A'
Qal
Ghadir el-Hazim
Tapline 6A
Ghadir el-Mal
Qal
Ghadir Abu es-Siyar
Hababiya No. 3
Hababiya No. 1
V
Qa' Khanna
JEBEL EL MUKHEZEN
B4
B3
JEBEL EL FULUQ
AZ-12
S-12
Wadi er-Ratam
Qasr el-Azraq
P-4
I-29
I-27
I-35
PA-4
PA-3
PA-5
AZ-1
AZ-11
AZ-8
AZ-13
AZ-9
PA-6
Azraq Druze
Azraq Sheshan
PA-2
P-11
PA-1A
B'
AZ-5
AZ-10
P-3
Wadi el-Harth
AZ-4
AZ-3
JEBEL EL-UWEINED
Qasr 'Amra
PAB-13
PAB-12
I-41
QA' EL-AZRAQ
P-1
Wadi al-Butm
PAB-15
PAB-17
PAB-8
PAB-7B
PAB-9
Qal
B5
Qa' al-Fira
TEL QARMA
P
Wadi Rajil
PAB-14
PAB-10
PAB-11
Shomari No.1
AG-1 (101)
104C
AG-3 (105-D)
P-5
AZ-14
P-6
AZ-23
Wadi Medeisisat
103B
Wadi esh-Shomari
AZ-15
AZ-22
Umari No.2
Umari No.3
AZ-21
Wadi ed-Dabi
EDH-DHAHKIYE
Wadi al-Bissi
Wadi ed-Drwah
Um Juleifat
AZ-19
AZ-29
Wadi ed-Dalyaneh
Wadi Jashah
el-Adla
al-Ghadaf
Wadi
Qasr Tuba
Jashah
SAUDI ARABIA



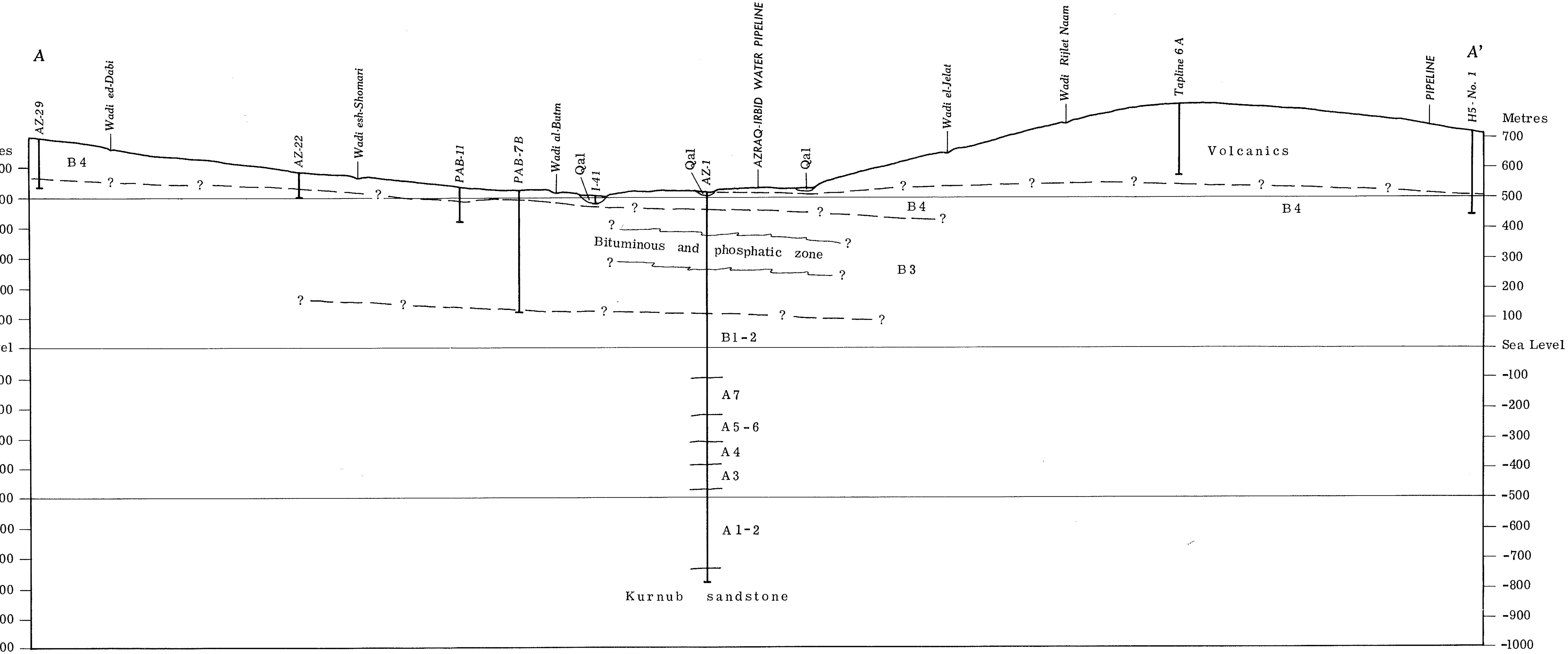
Druze Village
Druze Springs
Ancient canal
Druze salt evaporators
United Nations Base Camp and Weather Station
Druze Swamp
Azraq Pilot Farm
Sheshan salt evaporators
OB-1 Brine Well
Police Post
Said Ghanim Farm
Sheshan Swamp
Sheshan Village
Sheshan Springs
Baker-Harza Canal
Baker-Harza Swamp
Shomari Farm
QA' EL-AZRA
Road
Fence
Ancient w
Village
Canal
Salt evap
Area flood surface
Swamp a undiffe
Well
Spring
0
1
MILES

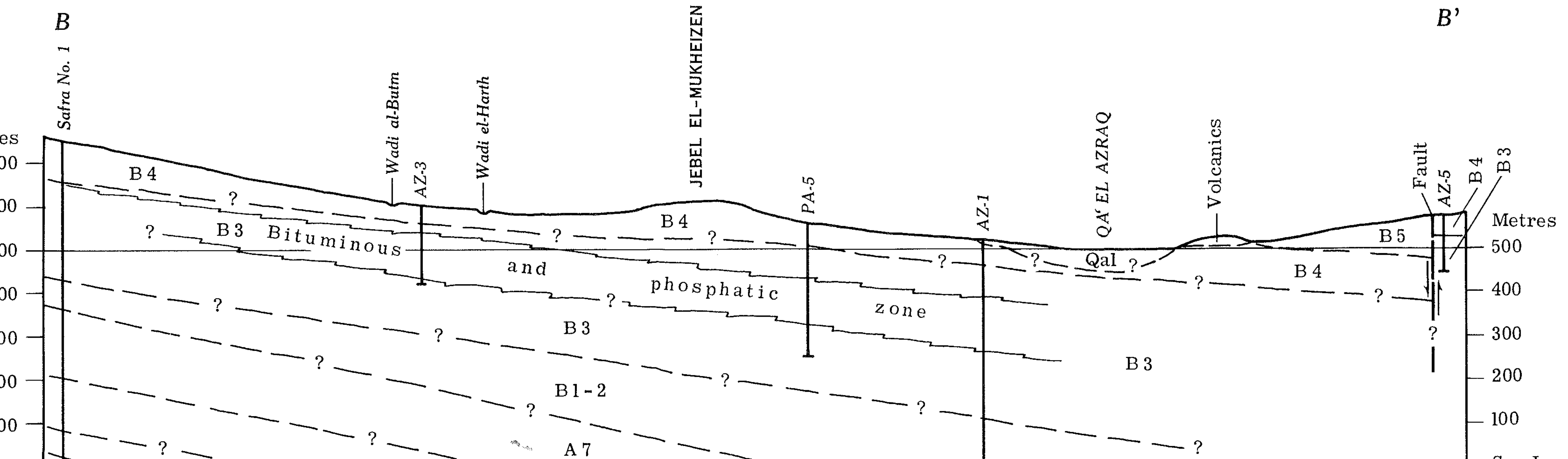


MAP 4. Map showing contours on the water-table and districting for control of drilling in the Azraq Basin.



MAP 5. Map showing chemical type of water in the Azraq Basin.

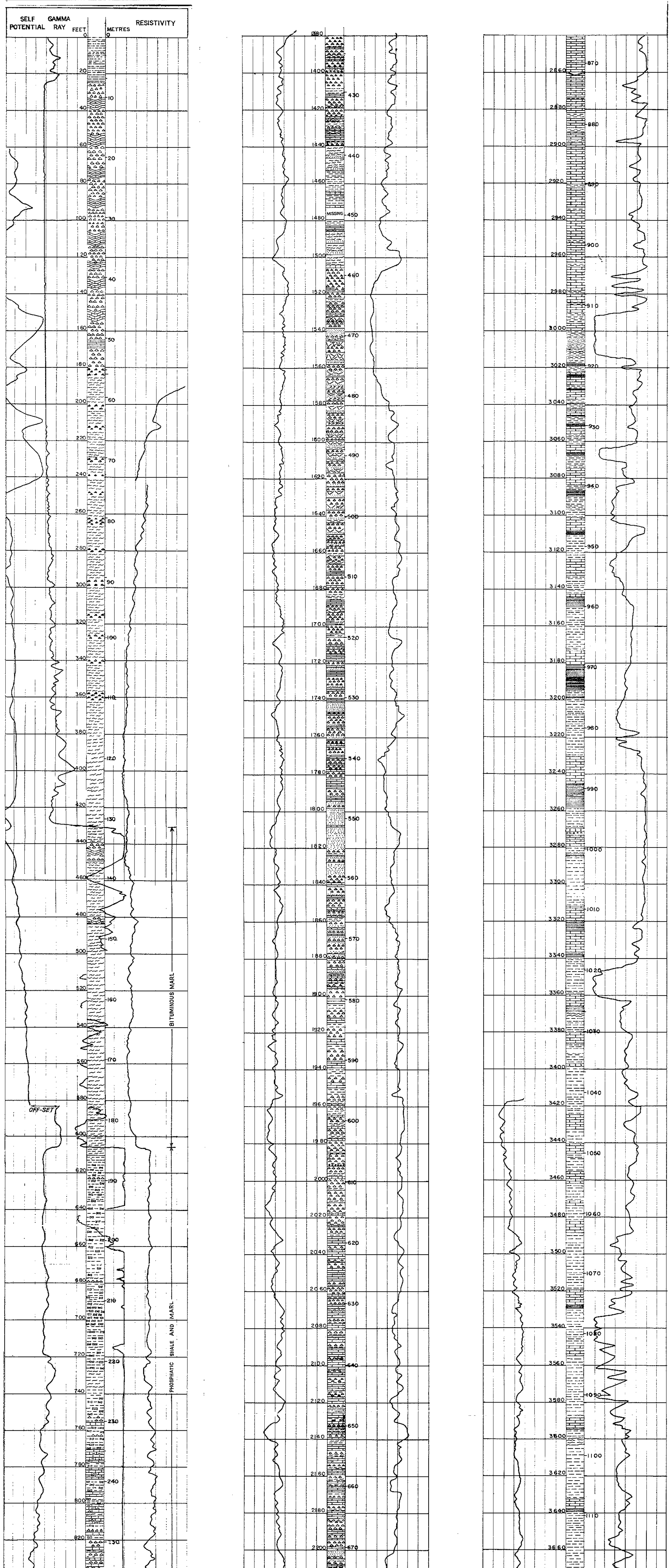

A
A'
AZ-29
Wadi ed-Dabi
AZ-22
Wadi esh-Shomari
PAB-11
PAB-7B
Wadi al-Butm
Qal
I-41
Qal
AZ-1
AZRAQ-IRBID WATER PIPELINE
Qal
Wadi el-Jelat
Wadi Rijlet Naam
Tapline 6 A
PIPELINE
H5 - No. 1
Metres
700
600
500
400
300
200
100
Sea Level
-100
-200
-300
-400
-500
-600
-700
-800
-900
-1000
B 4
Volcanics
B 4
B 4
Bituminous and phosphatic zone
B 3
B1 - 2
A 7
A 5 - 6
A 4
A 3
A 1 - 2
Kurnub sandstone

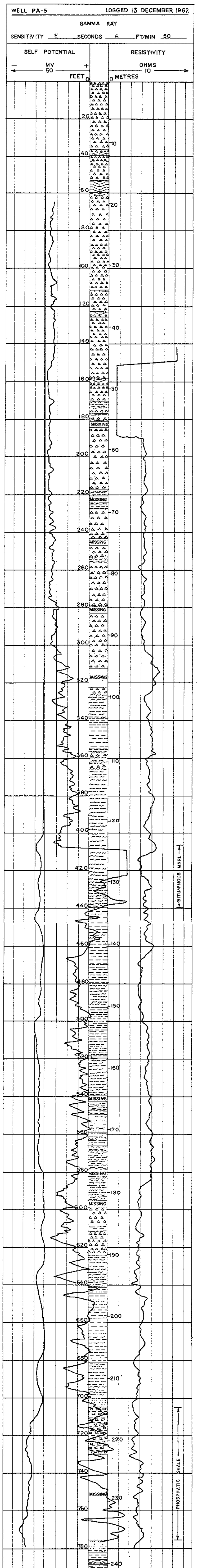

B
B'
Safra No. 1
Wadi al-Butm
AZ-3
Wadi el-Harth
JEBEL EL-MUKHEIZEN
PA-5
AZ-1
QA' EL AZRAQ
Volcanics
Fault
AZ-5
B 4
B 3
Metres
500
400
300
200
100
B 4
B 3 Bituminous
and
phosphatic
zone
B 4
Qal
B 5
B 4
B 3
B 3
B1 - 2
A 7

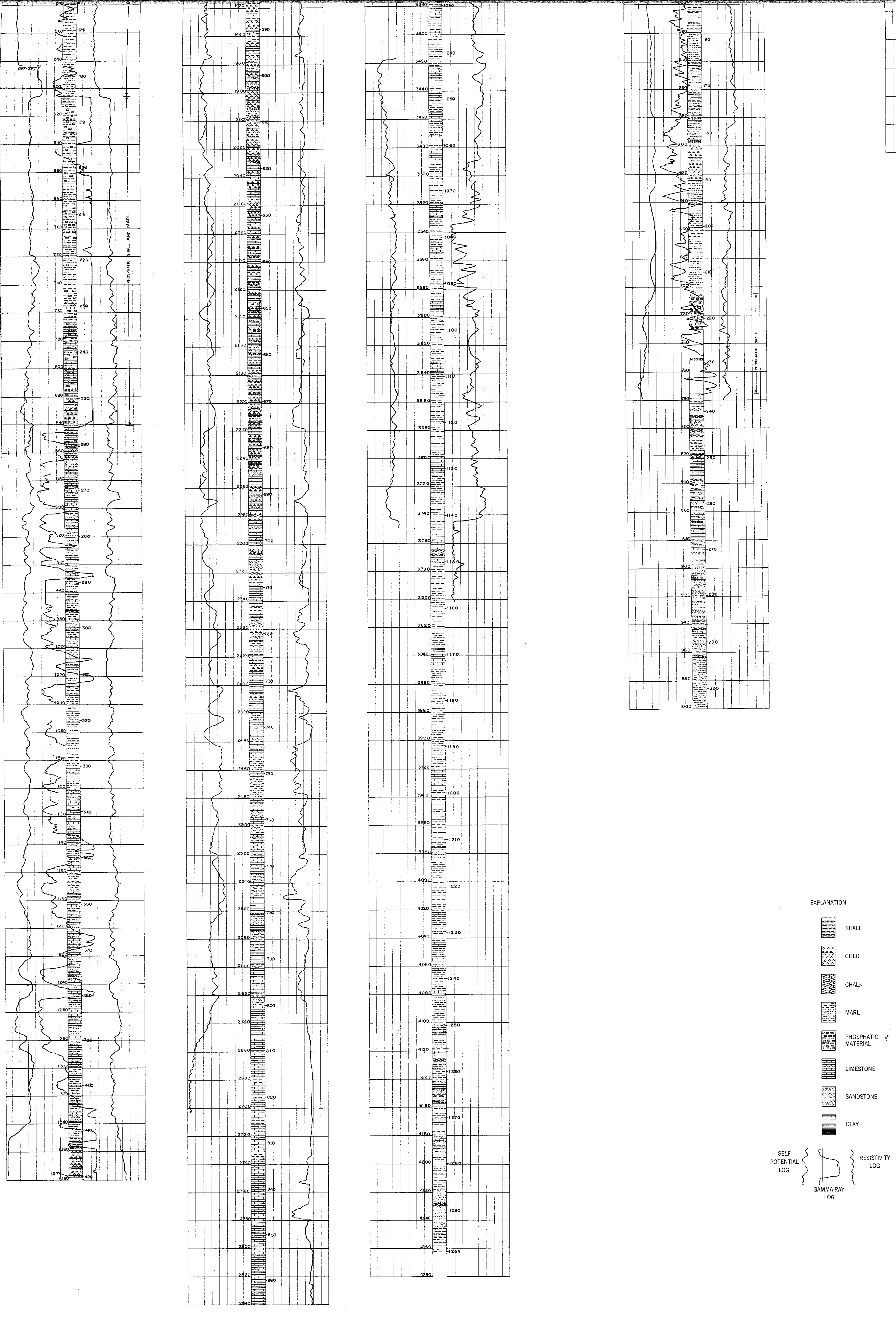
WELL AZ-1

DATE	FROM-TO (FEET)	RESISTIVITY (OHMS)	SELF POTENTIAL	GAMMA RAY POSITION	TIME CONST. (MIN.)	SPEED OF LOGGING
12/12/1962	0 – 600	10	50	E	6	25 FT/MIN
18/ 2/1963	600 –1376	20	200	B	6	25 "
19/ 7/1963	1376 –2736	50	200	E	6&4	25 "
16/ 9/1963	2736 –3800	20	200	E	6	25 "

ALL MEASUREMENTS WERE MADE FROM THE ROTARY DRILL TABLE, WHICH WAS 4.2 FEET ABOVE LAND SURFACE. THE GAMMA RAY WAS INOPERATIVE FROM 1380 TO 3800 FEET. THE SELF-POTENTIAL PEN WAS PREVENTED FROM TRACING LATERALLY WHEN IT TOUCHED THE INOPERATIVE GAMMA-RAY PEN FROM 2700 TO 3416 FEET AND FROM 3750 TO 3800 FEET.







EXPLANATION
SHALE
CHERT
CHALK
MARL
PHOSPHATIC MATERIAL
LIMESTONE
SANDSTONE
CLAY
SELF-POTENTIAL LOG
RESISTIVITY LOG
GAMMA-RAY LOG
PHOSPHATIC SHALE AND MARL
PHOSPHATIC SHALE
OFF-SET
MISSING